CUORE-0 results and prospects for the CUORE experiment

O.Cremonesi
on behalf of the CUORE Collaboration

INFN - Sez. Milano Bicocca

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Neutrinoless double beta decay

Rare nuclear decay

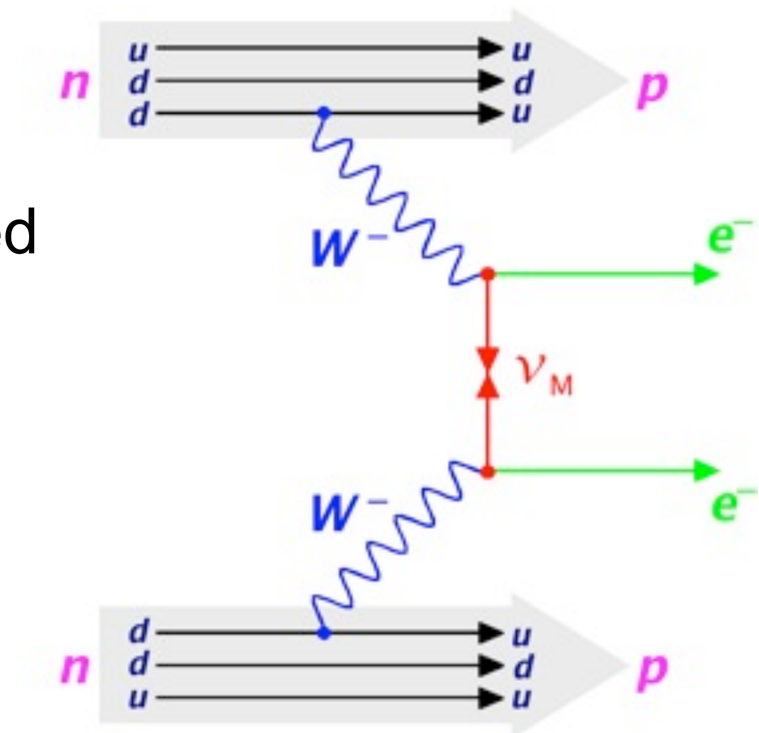
(A,Z) → (A,Z+2) + 2e⁻

Unique practical way to answer one of the most relevant unresolved questions:

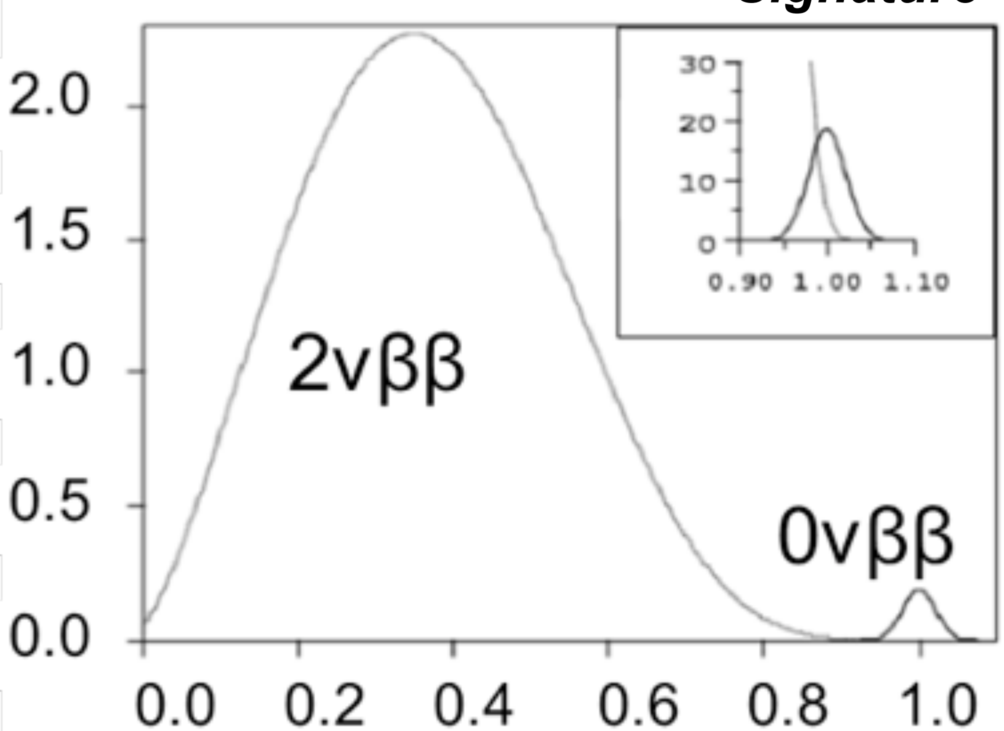
→ is the neutrino a Majorana particle?

If observed provides important informations:

- lepton number violation
- absolute neutrino mass scale
- Majorana phases



Signature



N_B = number of background counts in the ROI along the measure time

Sensitivity

$N_B \gg 1$

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

$N_B \leq O(1)$ → "zero

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

t_{meas}	measuring time [y]
M	detector mass [kg]
ε	detector efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energy resolution [keV]
bkg	background [c/keV/y/kg]

CUORE @ LNGS

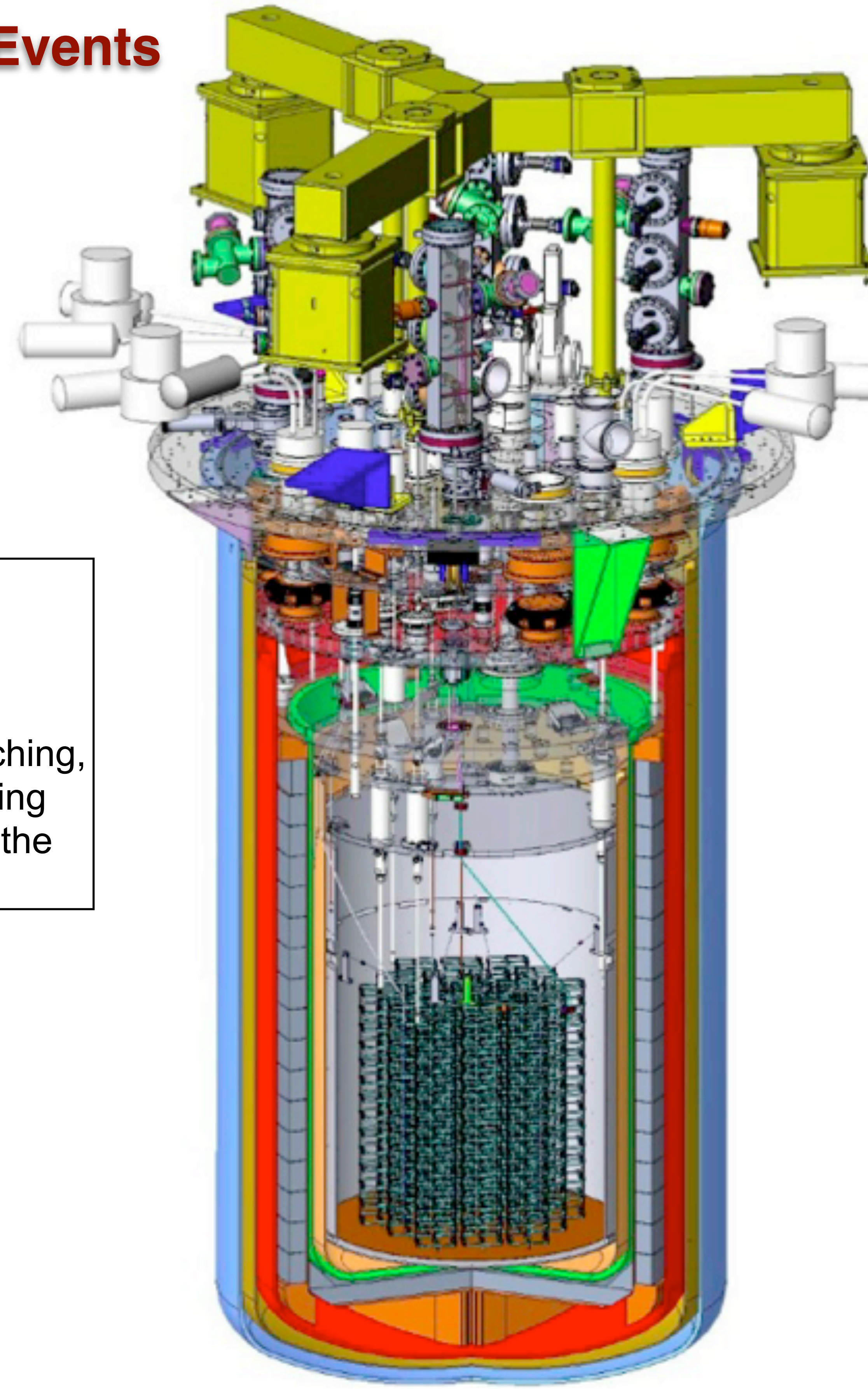
Cryogenic Underground Observatory for Rare Events

CUORE detector

- **988 TeO_2 crystals run as a bolometer array**
  - 5x5x5 cm^3 crystal, 750 g each
- **19 Towers; 13 floors; 4 modules per floor**
  - 741 kg total - 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- **Excellent energy resolution of bolometers**
- **Radio-pure material and clean assembly to achieve low background at ROI**
  - strict radiopurity control protocol to limit bulk and surface contaminations in crystal production
  - transportation at sea level to LNGS
  - bolometric test to check performances and radio-purity
  - TECM protocol (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) for copper surface cleaning
  - limited exposure to cosmic rays: underground storage of the copper parts in between production and cleaning

Complex cryogenic set-up

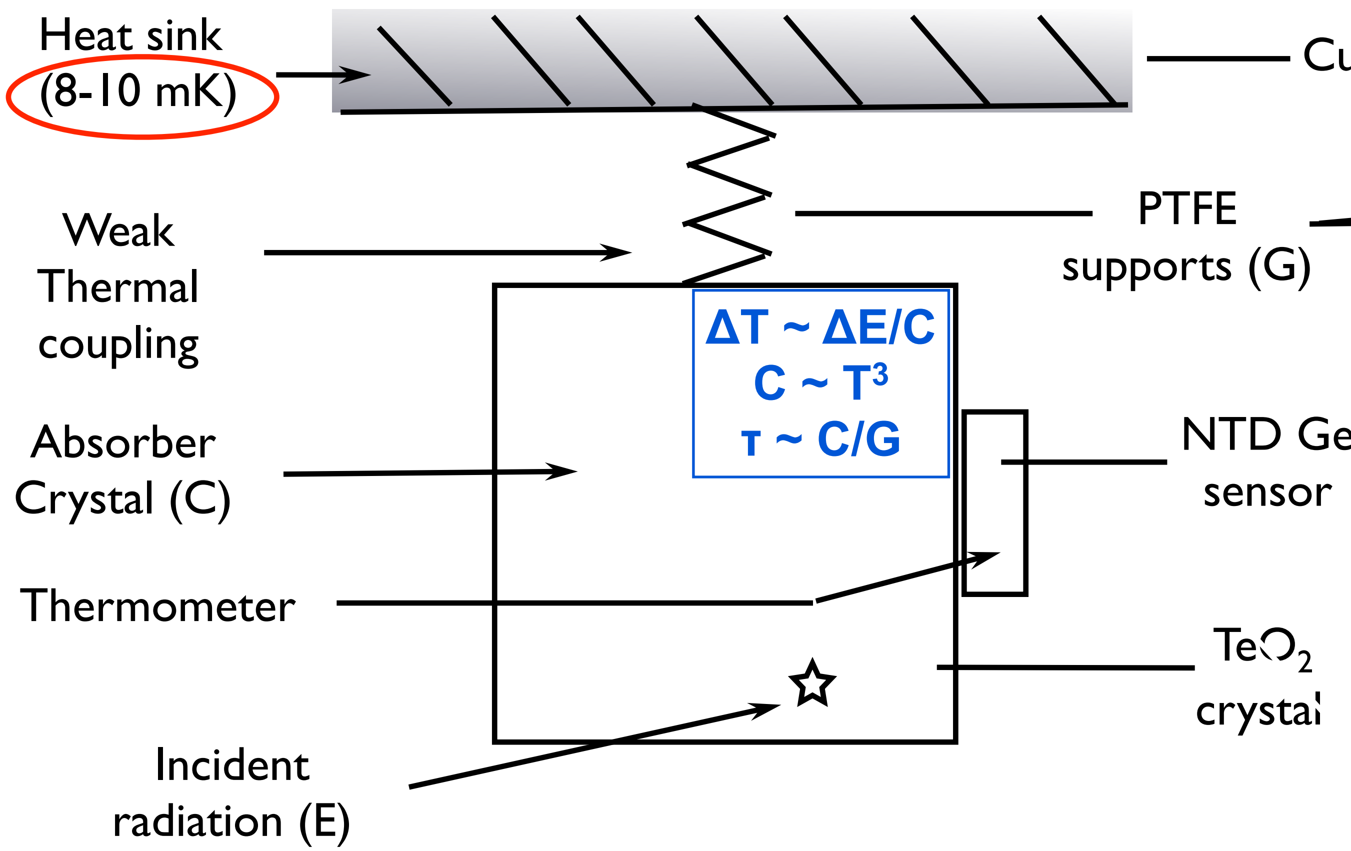
- **Fully cryogen-free system:**
  - custom cryostat
  - 5 pulse tubes
  - a powerful dilution refrigerator and
- **~10 mK operating temperature**
- **Independent suspension of the detector array**
- **An embedded detector calibration system**
- **Radio-pure materials**
- **Heavy low temperature shield**

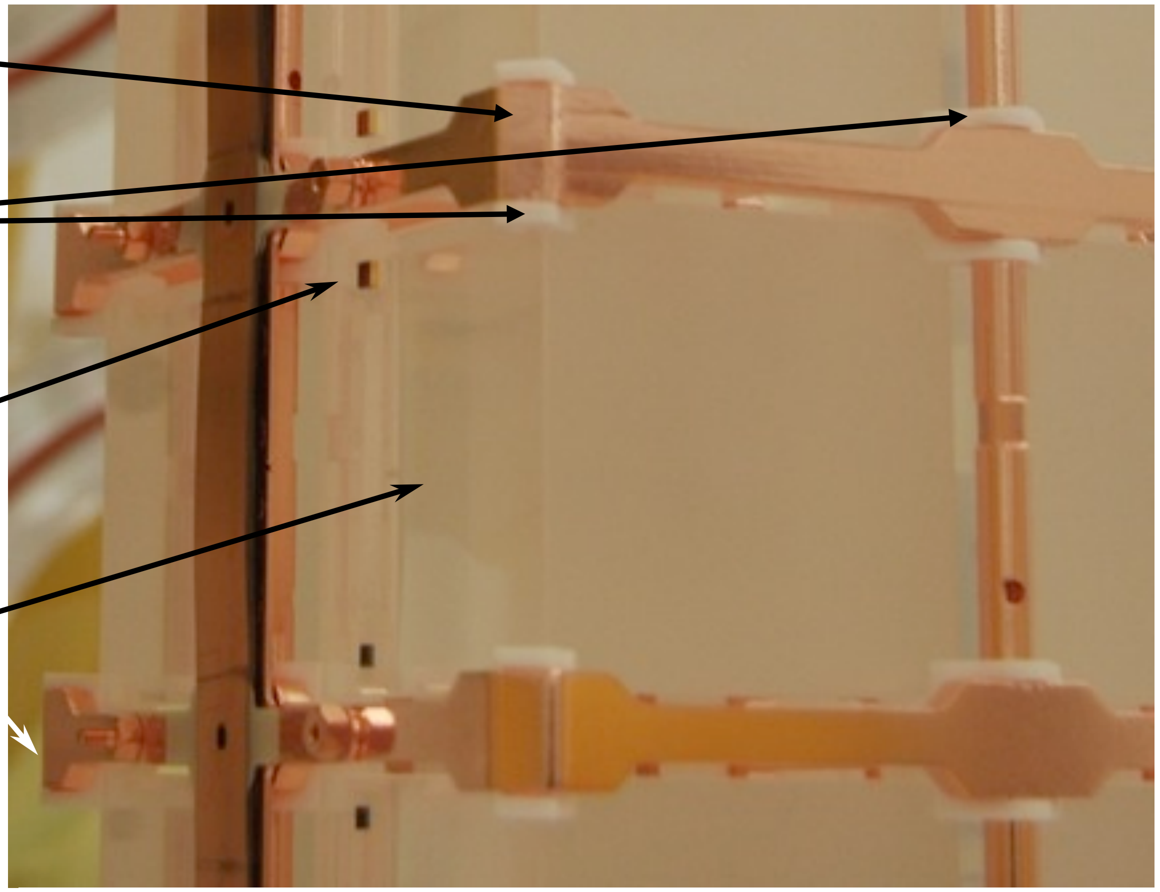


CUORE Collaboration

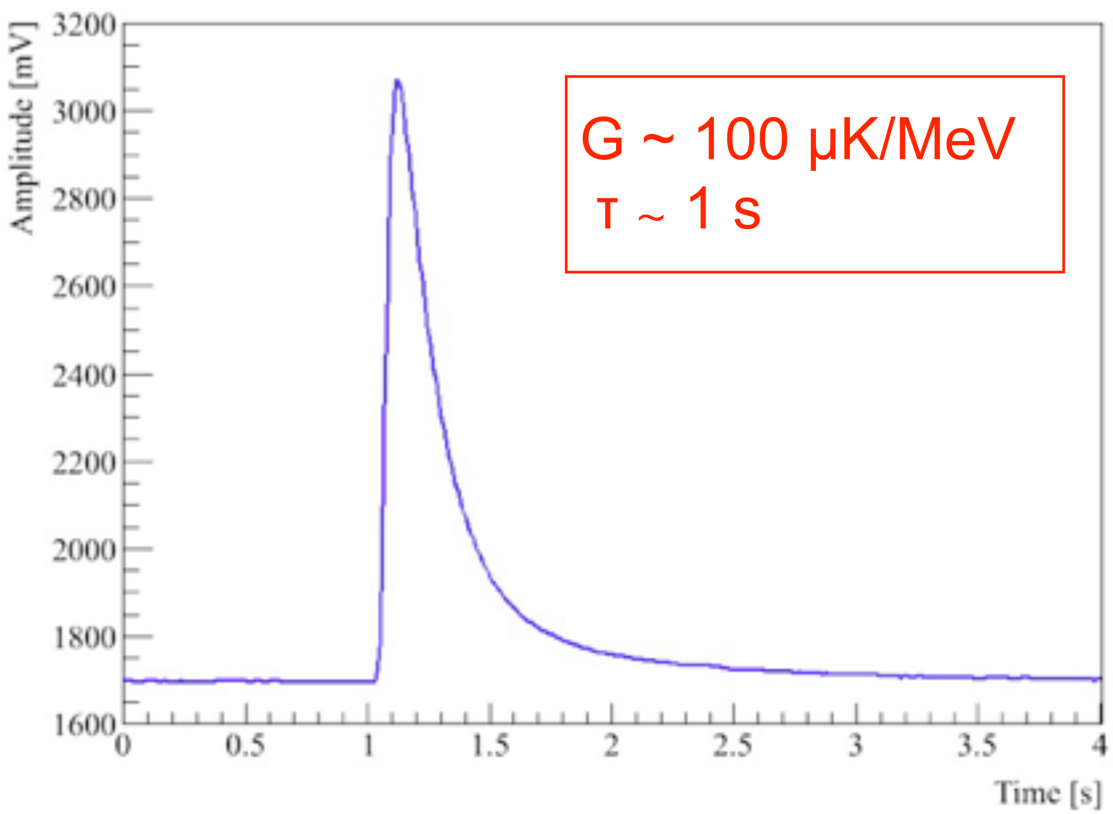
- 19 groups
    - Italy
    - USA
    - China
    - France
- 148 collaborators
- 117 researchers

Bolometric concept

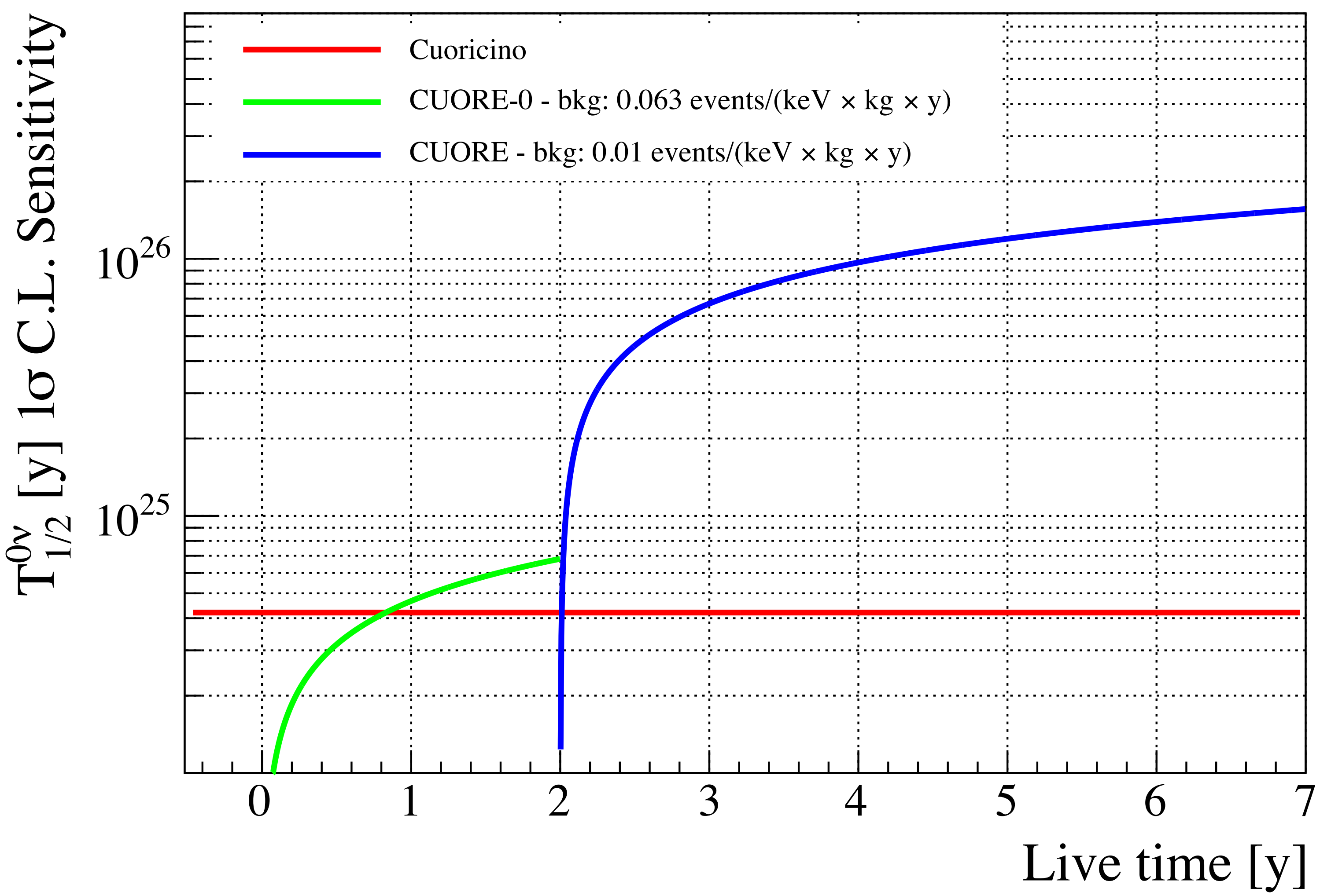


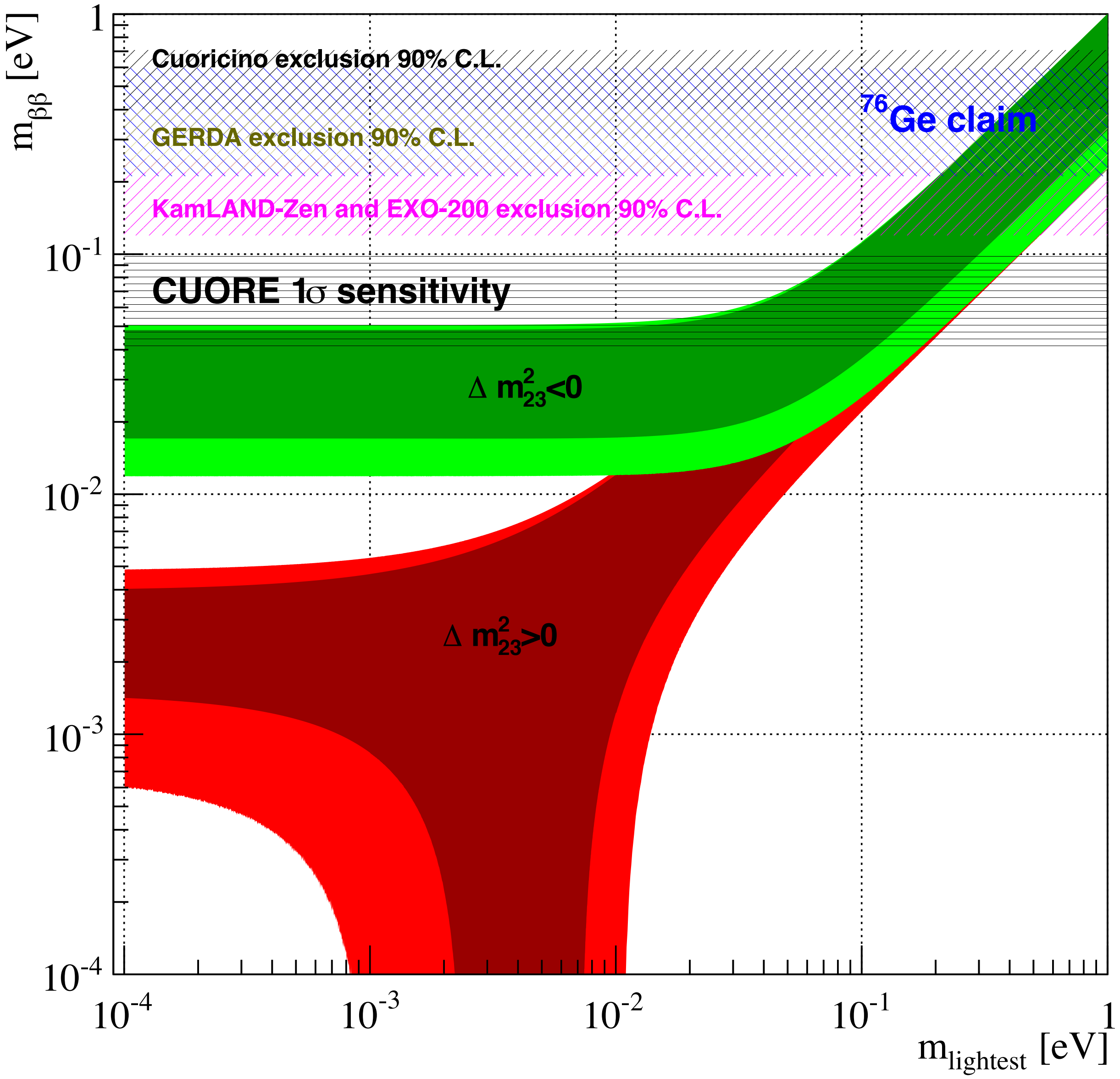


- Excellent energy resolution: $(k_B C T^2)^{1/2}$
- Calorimetric approach
- Wide choice of the absorber material
- Large mass arrays



CUORE sensitivity





Design sensitivity goal:

- background rate of 10^{-2} counts/(keV kg y)
- 5 keV FWHM
- 5 years of live time

Corresponding to 1σ sensitivity

- $S_{1/2}(0\nu\beta\beta) = 1.6 \times 10^{26}$ y (9.5×10^{25} y @ 90% CL)

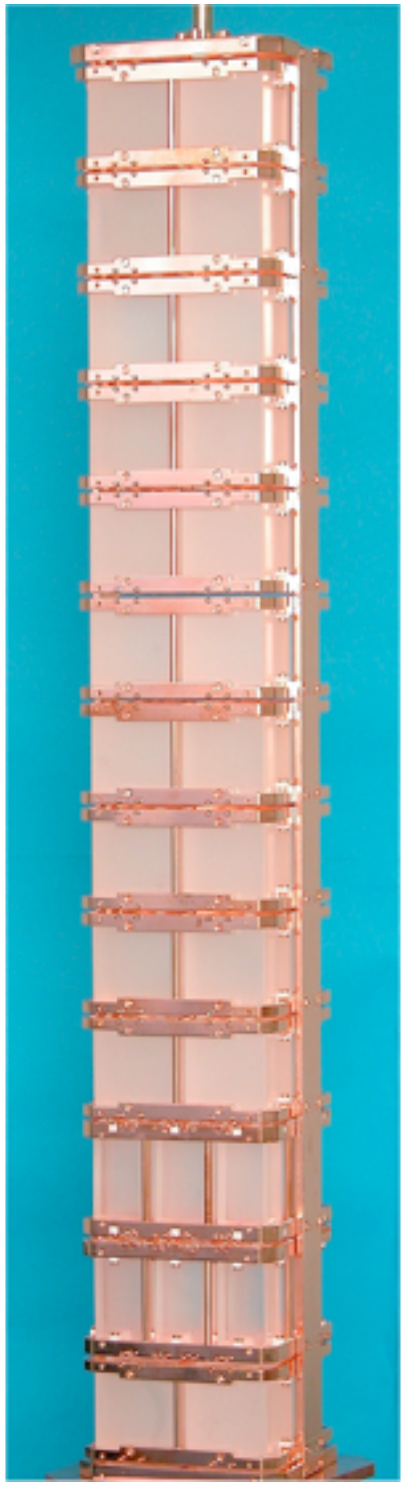
or equivalently in terms of effective Majorana mass down to

- $\langle m_{ee} \rangle \sim$ 40-100 meV

- ***0νββ***
- ***Dark matter***
- ***Rare nuclear decays***

A phased program

CUORICINO
2003

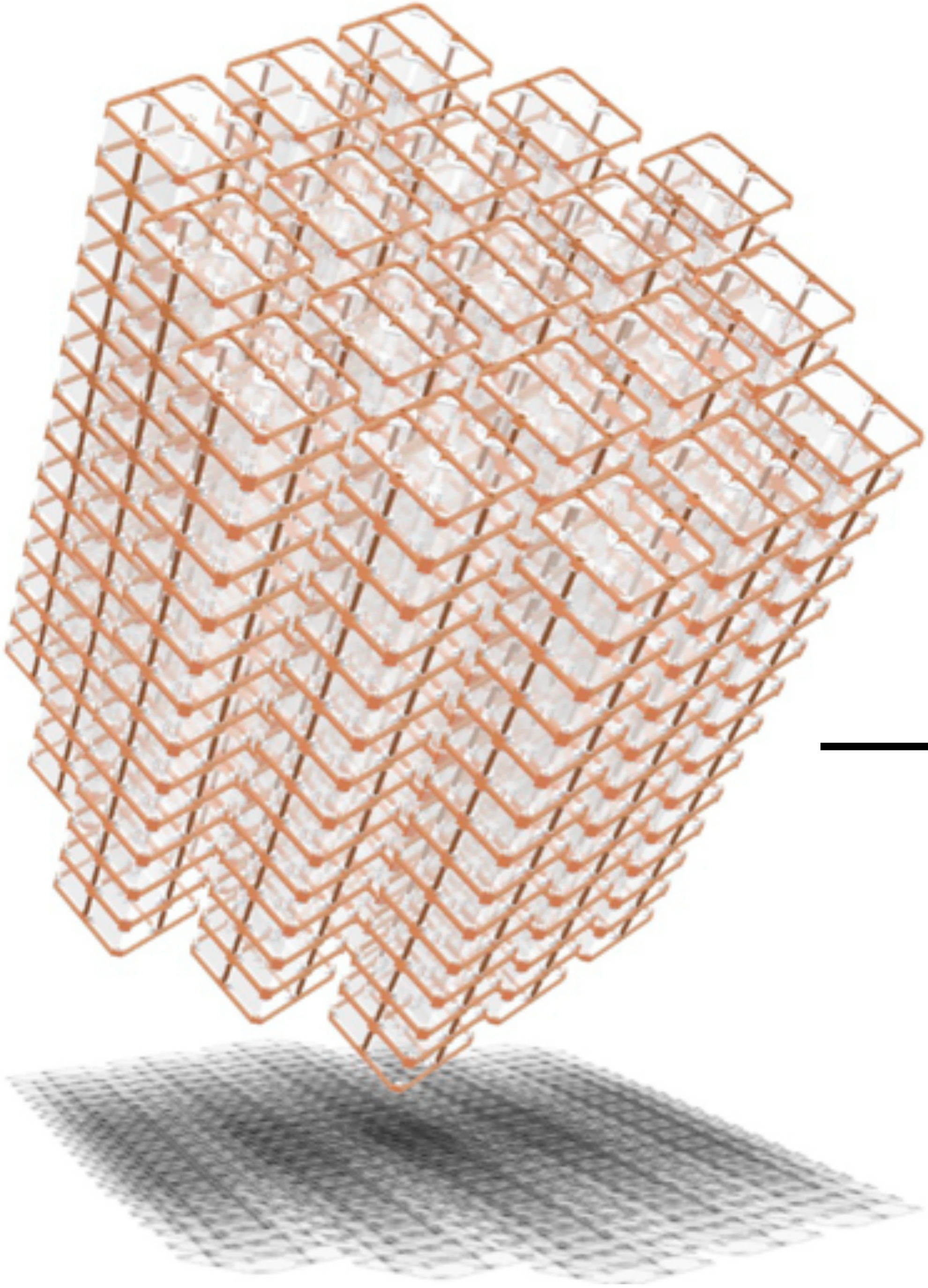


→

CUORE0
2012

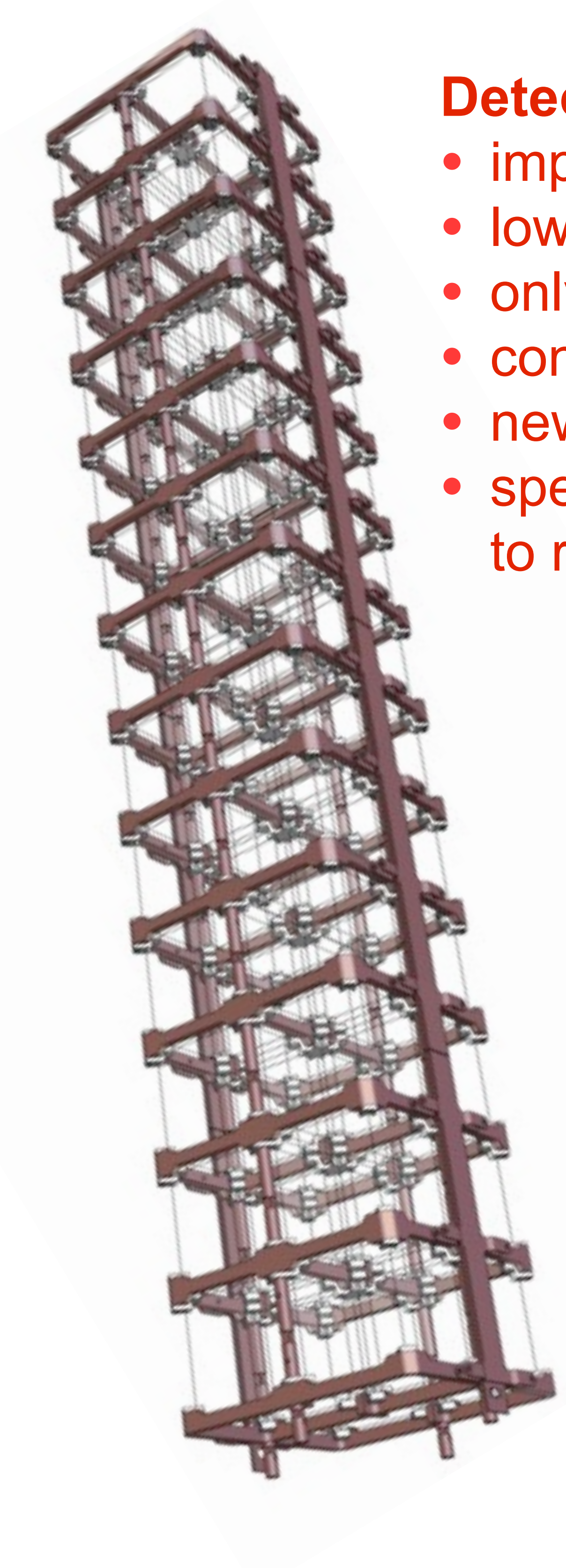
→

CUORE
2015



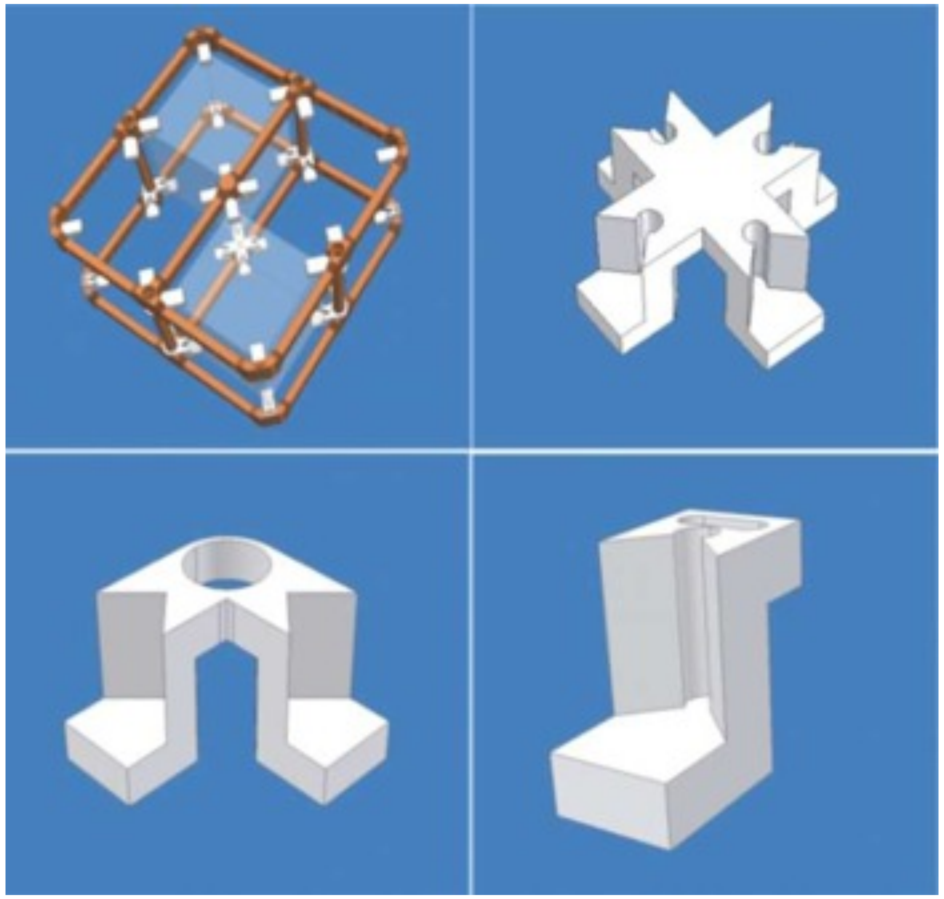
→ ?

CUORE detector



Detector design

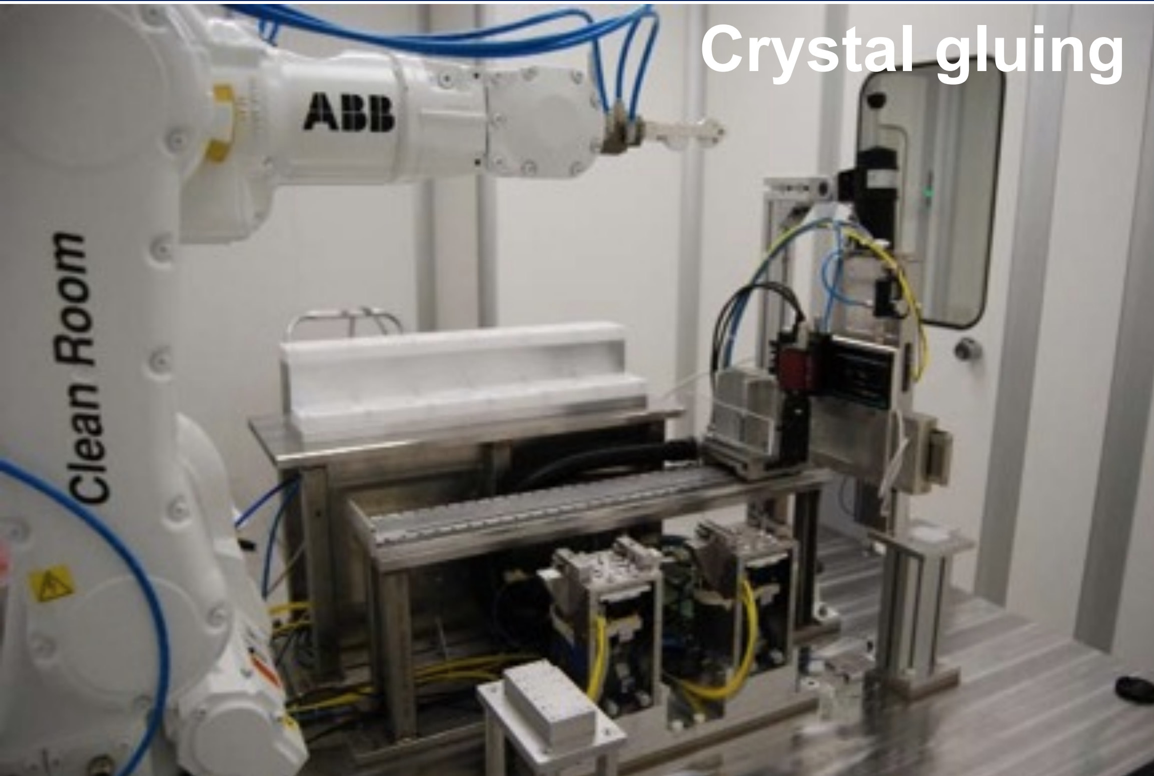
- improved modular structure
- lower amount of passive materials
- only selected materials (copper and PTFE)
- controlled thermal and mechanical coupling
- new single module concept: tower
- specially designed copper cleaning techniques to reduce Cu surface contamination



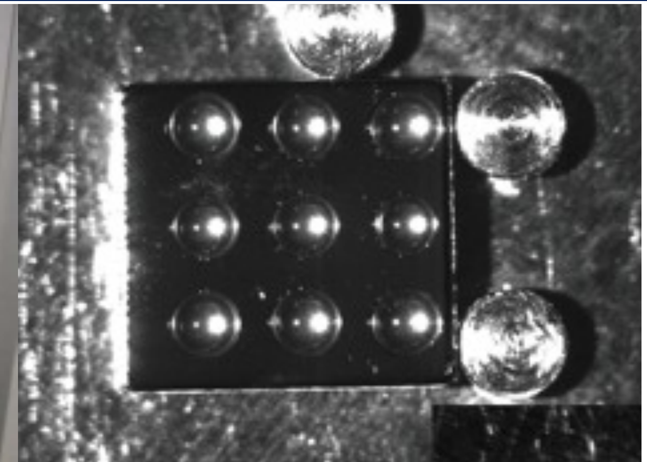
Tower assembly

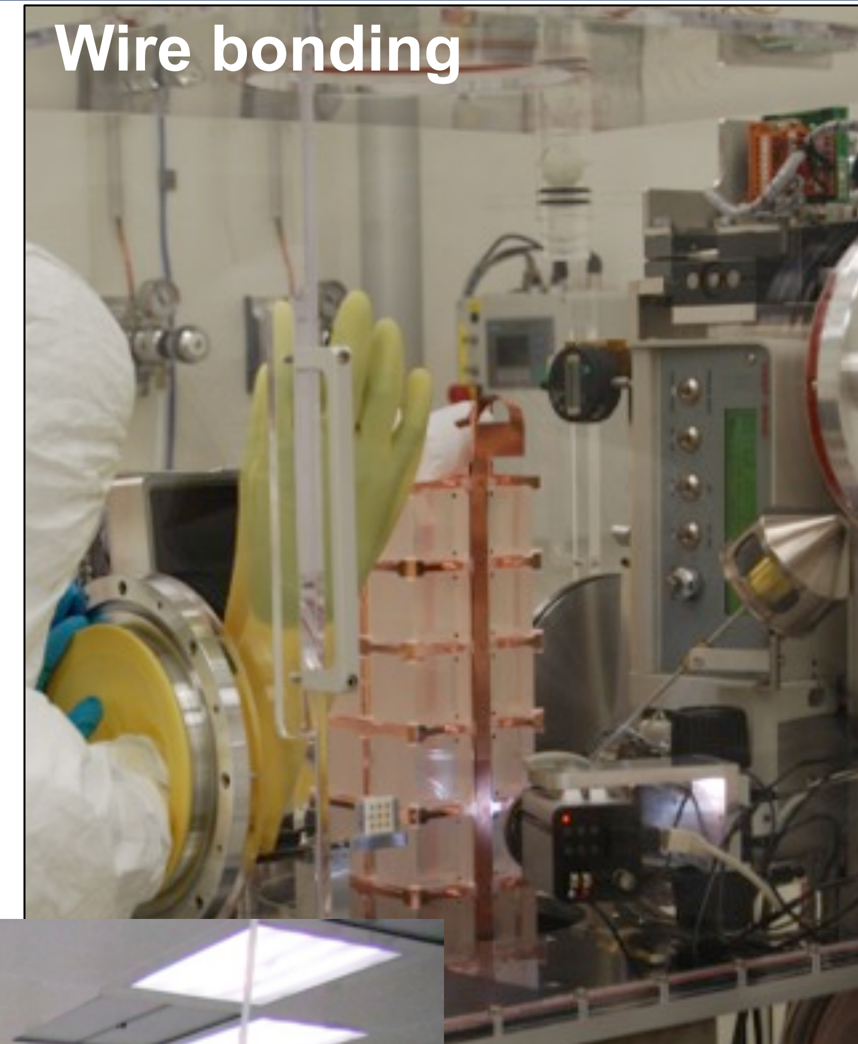
- carried out inside the clean room on the second floor of the CUORE building
- organized in 4 main operations
  1. Cleaning of the assembly tools and equipment
  2. Gluing of thermistors and heaters to the TeO_2 crystals;
  3. Mechanical assembly of the glued crystals, copper, PTFE, and wire strips
  4. Bonding of Au wires directly on thermistors, heaters and contact pads
- set of specially designed Glove Boxes
  - Rn free atmosphere
  - strict control of materials
  - reproducible protocol

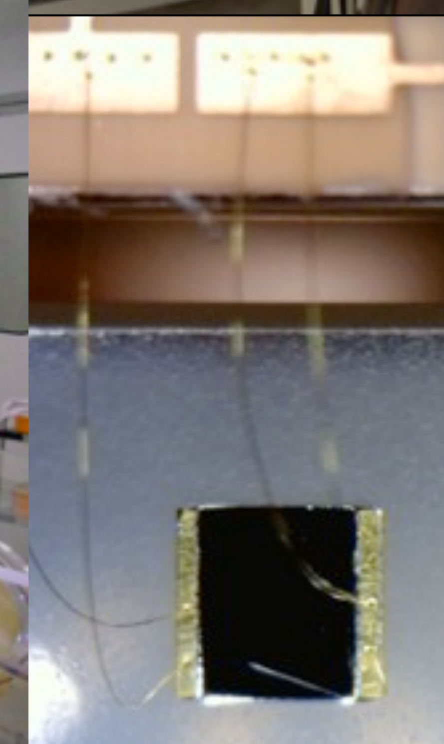
Tower assembly

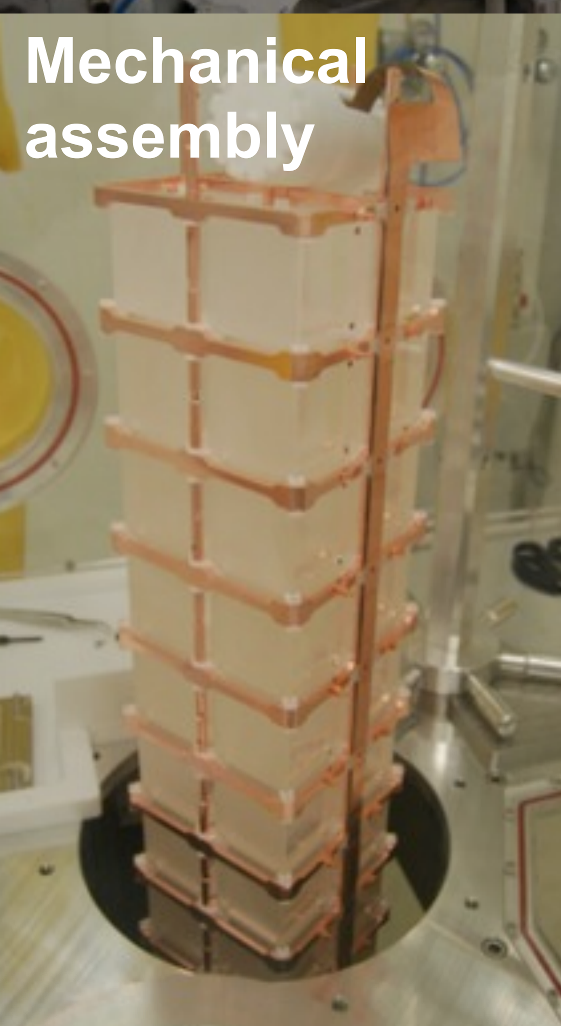


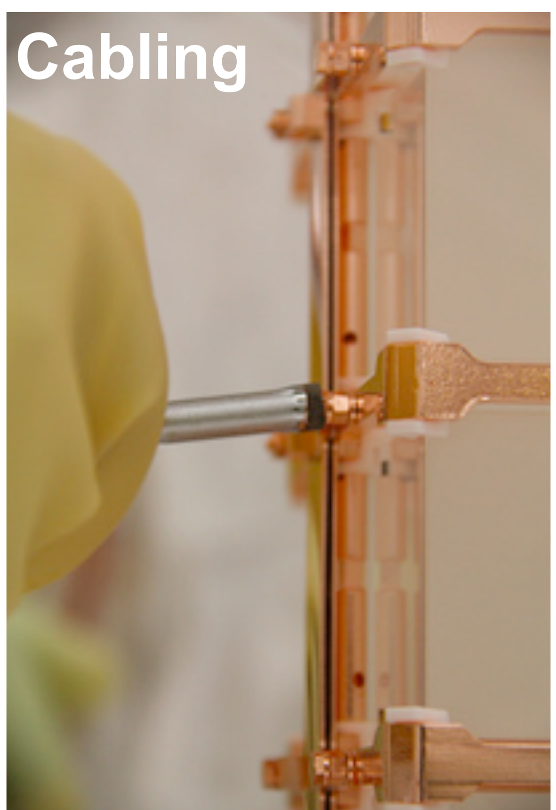
Crystal gluing




Wire bonding

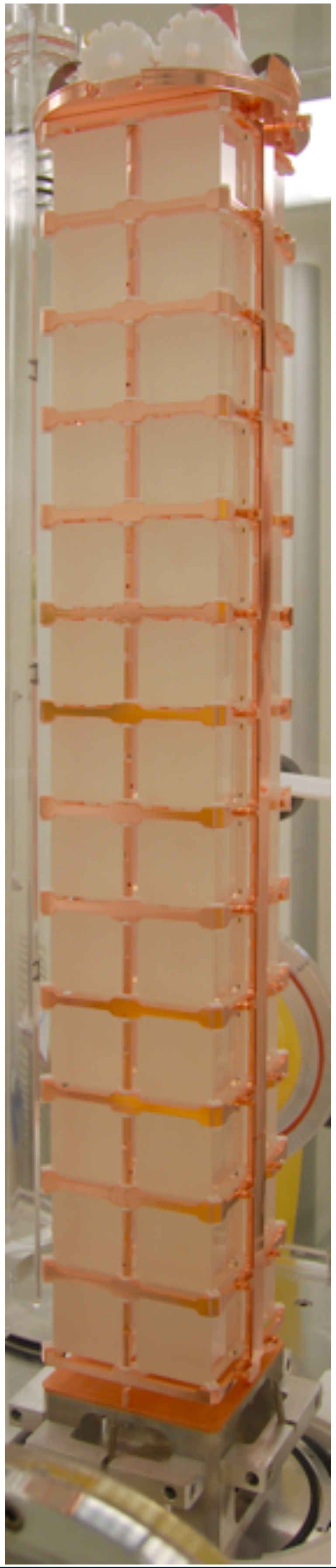



Mechanical assembly


Cabling


Clean room

CUORE-0



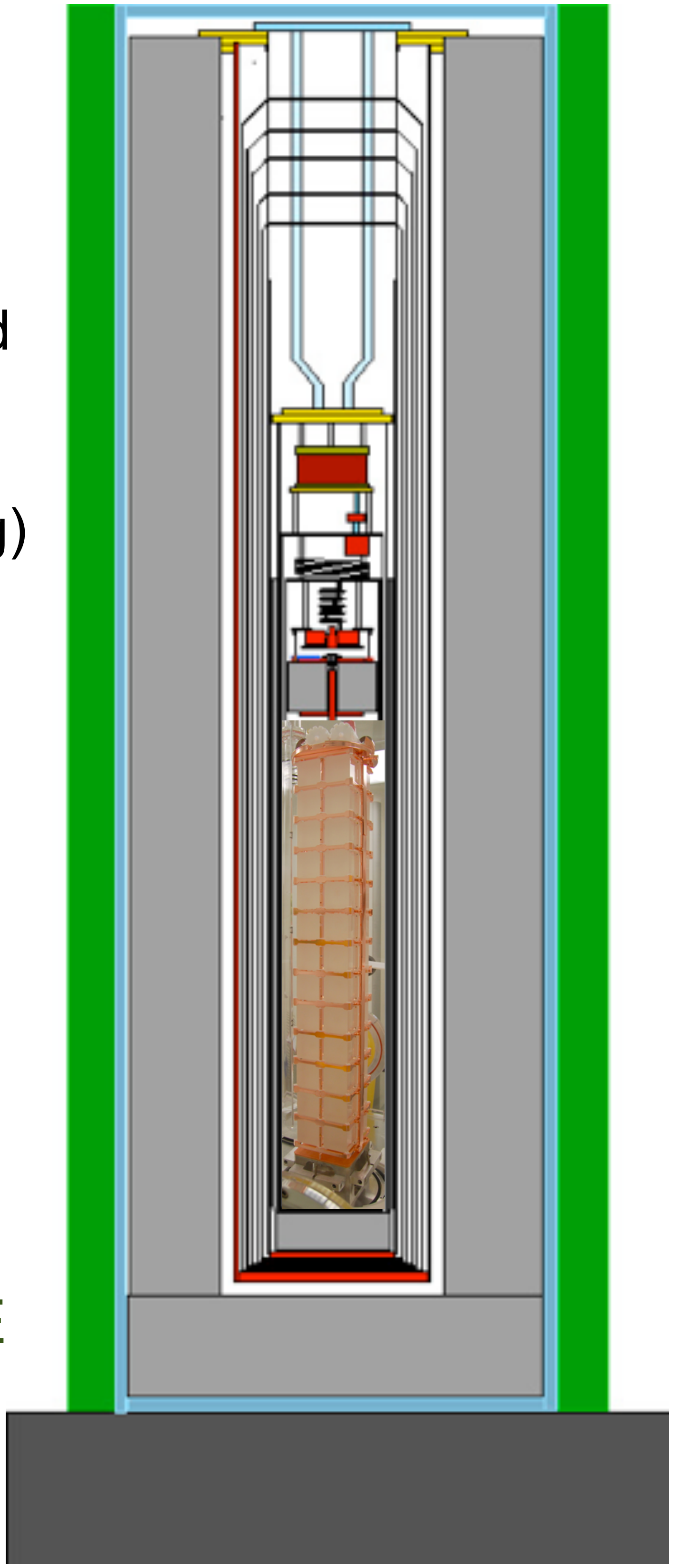
1 CUORE tower

- 52 TeO_2 5x5x5 cm^3 bolometers
- 13 floors of 4 crystals each
- **total mass:** 39 kg (11 kg of ^{130}Te)

- All detector components manufactured, cleaned and stored with same protocols defined for CUORE
- Assembled with the same procedures of CUORE:
  - dedicated class 1000 clean room (underground building)
  - all steps of the assembly (crystal gluing, mounting, cabling, bonding) performed under nitrogen inside special glove boxes.
- Operated inside the 25-year-old Cuoricino cryostat at LNGS.
- Low temperature roman lead shield

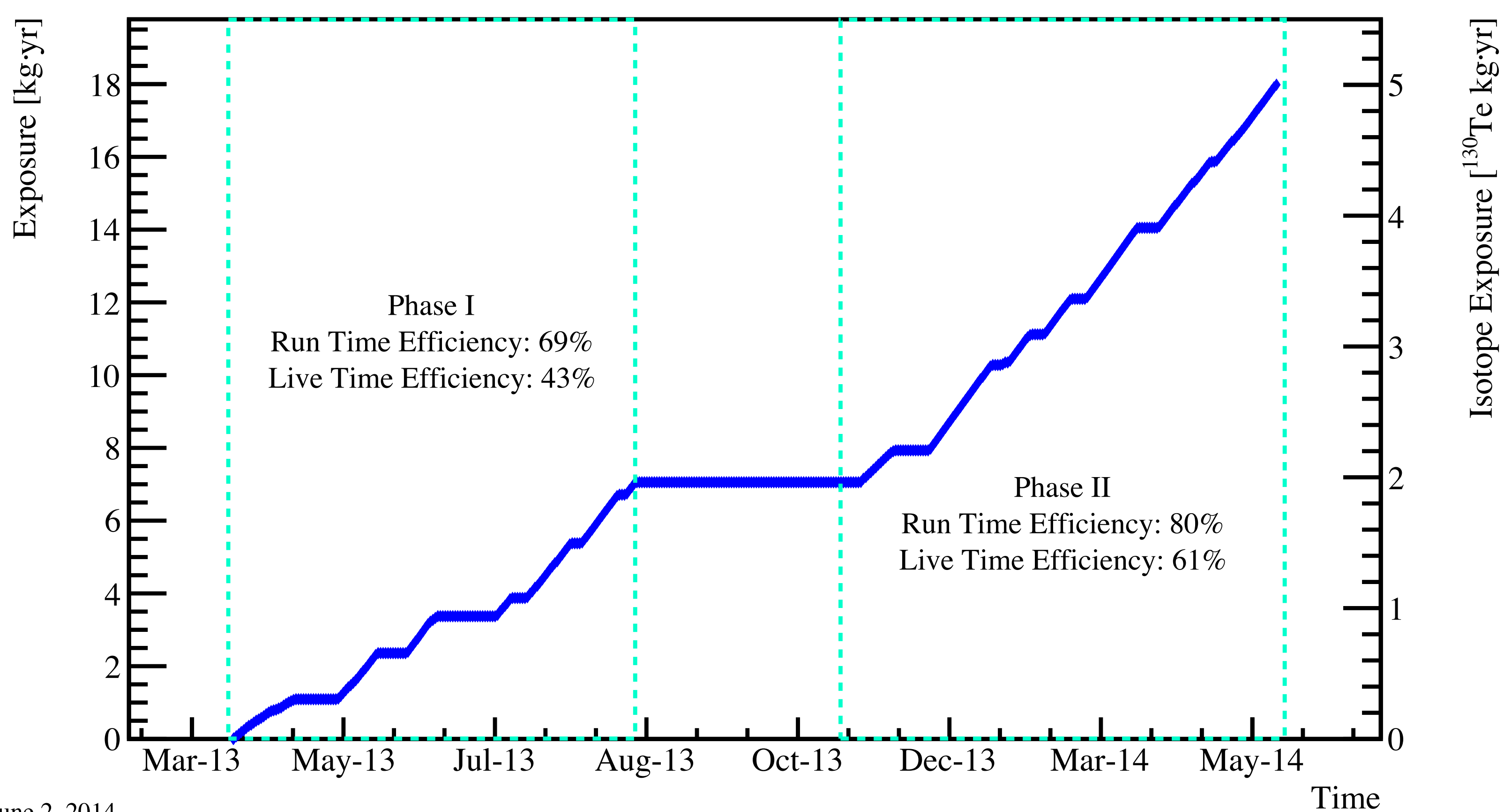
Goals:

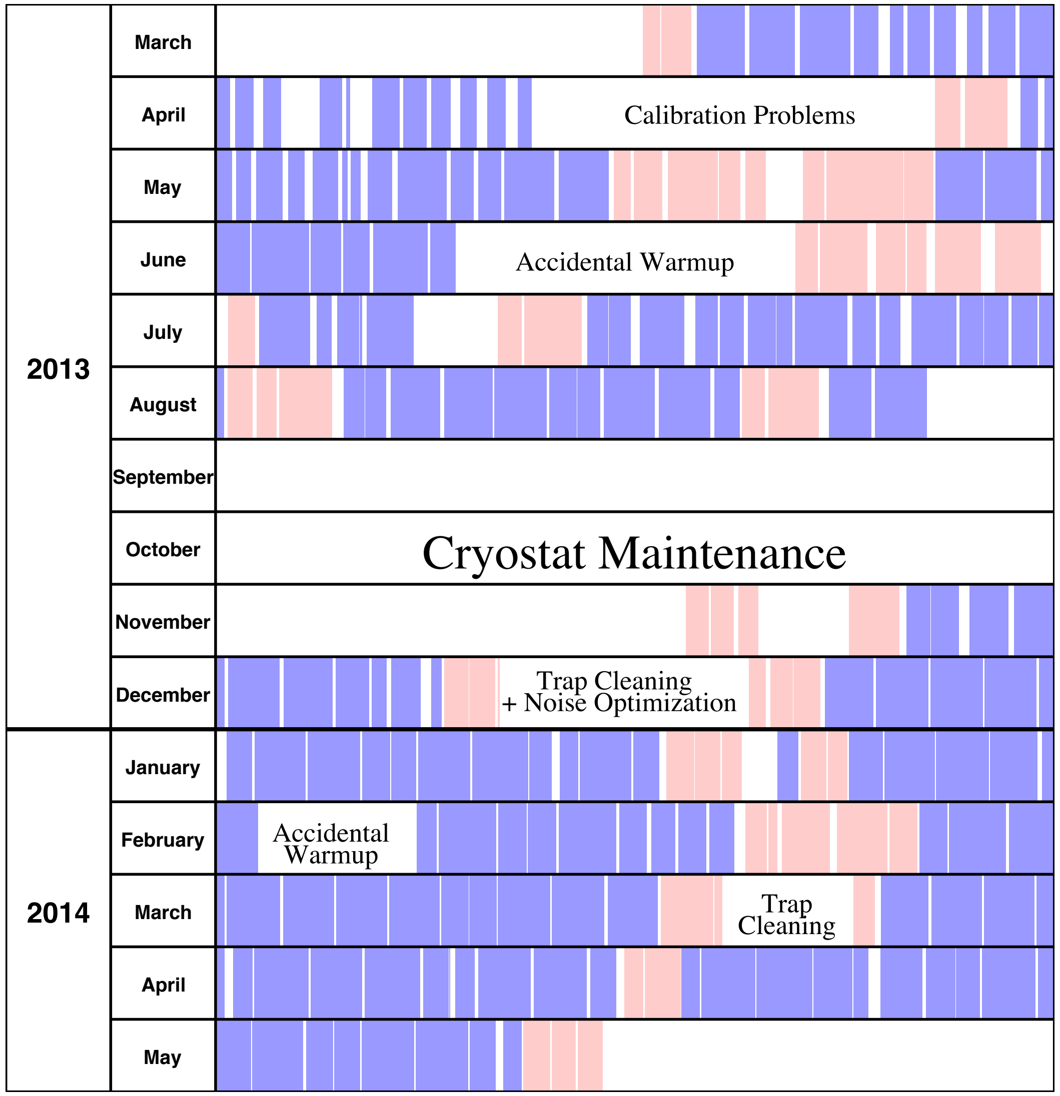
- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Operating as independent experiment while CUORE is under construction
- Demonstrate potential for DM detection



CUORE-0 data taking

- **August 2012**: base T reached
  ... problems with old Cuoricino cryostat
- **March 2013**: start data taking (Phase I)
- **September 2013**: first results are released (→ arXiv:1402.0922)
- **October 2013**: long maintenance stop
- **November 2013**: background data taking restarted (Phase II)
  → **improved conditions**
  - Longer system lifetime (no warm-up required so far)
  - Better noise conditions
    - Improved energy resolution
    - Lower Threshold
  - Data analysis tools optimization
  - Stable background values



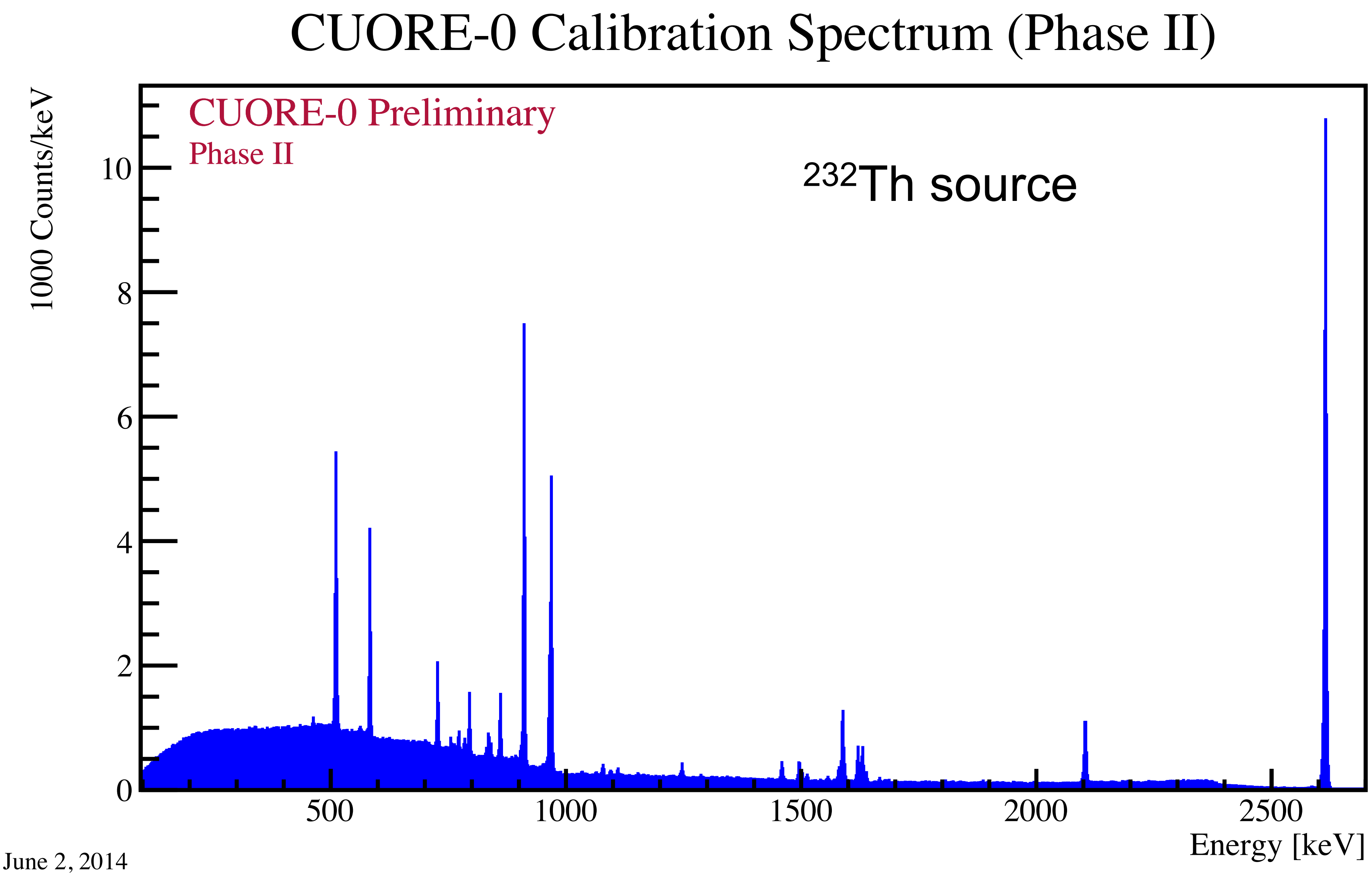


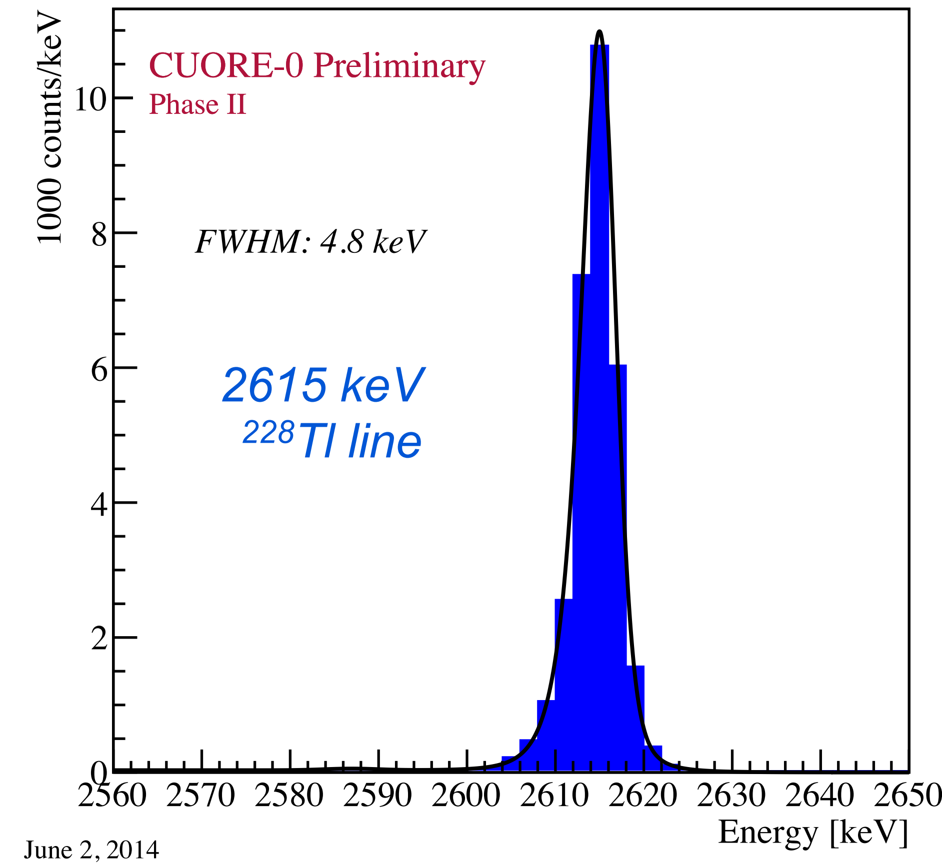
- Background measurements
- Calibration runs

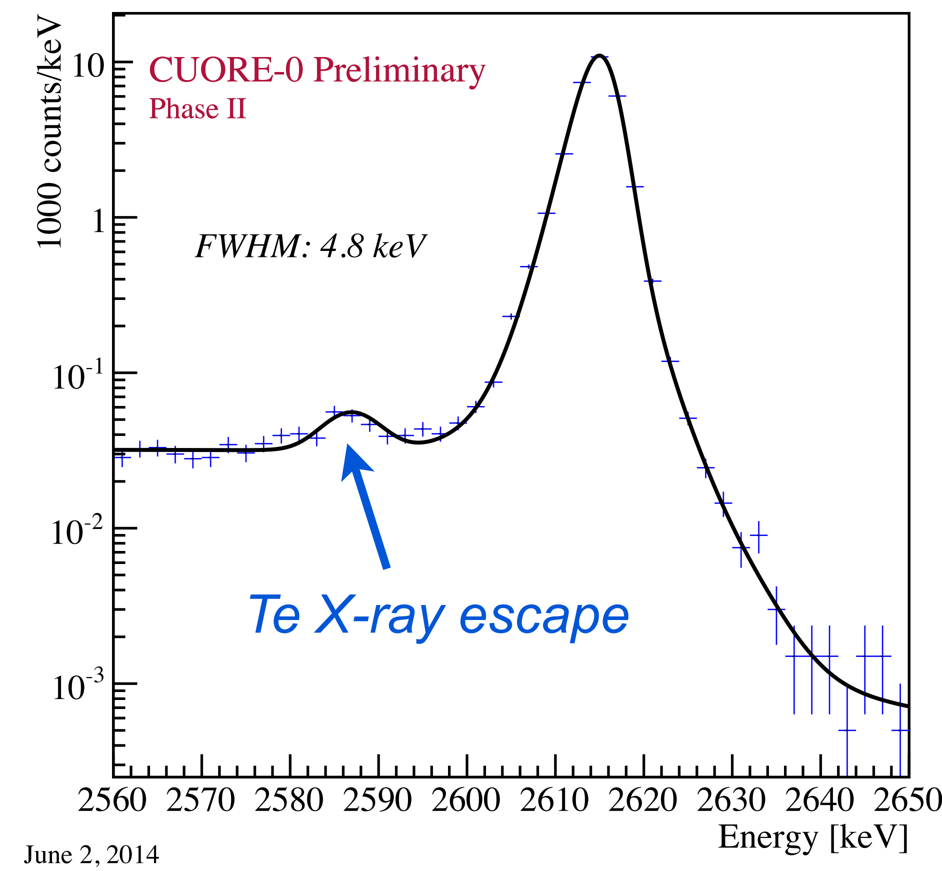
CUORE-0 energy resolution: phase II

- Calibration runs are carried out at the beginning and end of each data set
- Two thoriated strings are positioned just outside the cryostat OVC on opposite sides of the tower

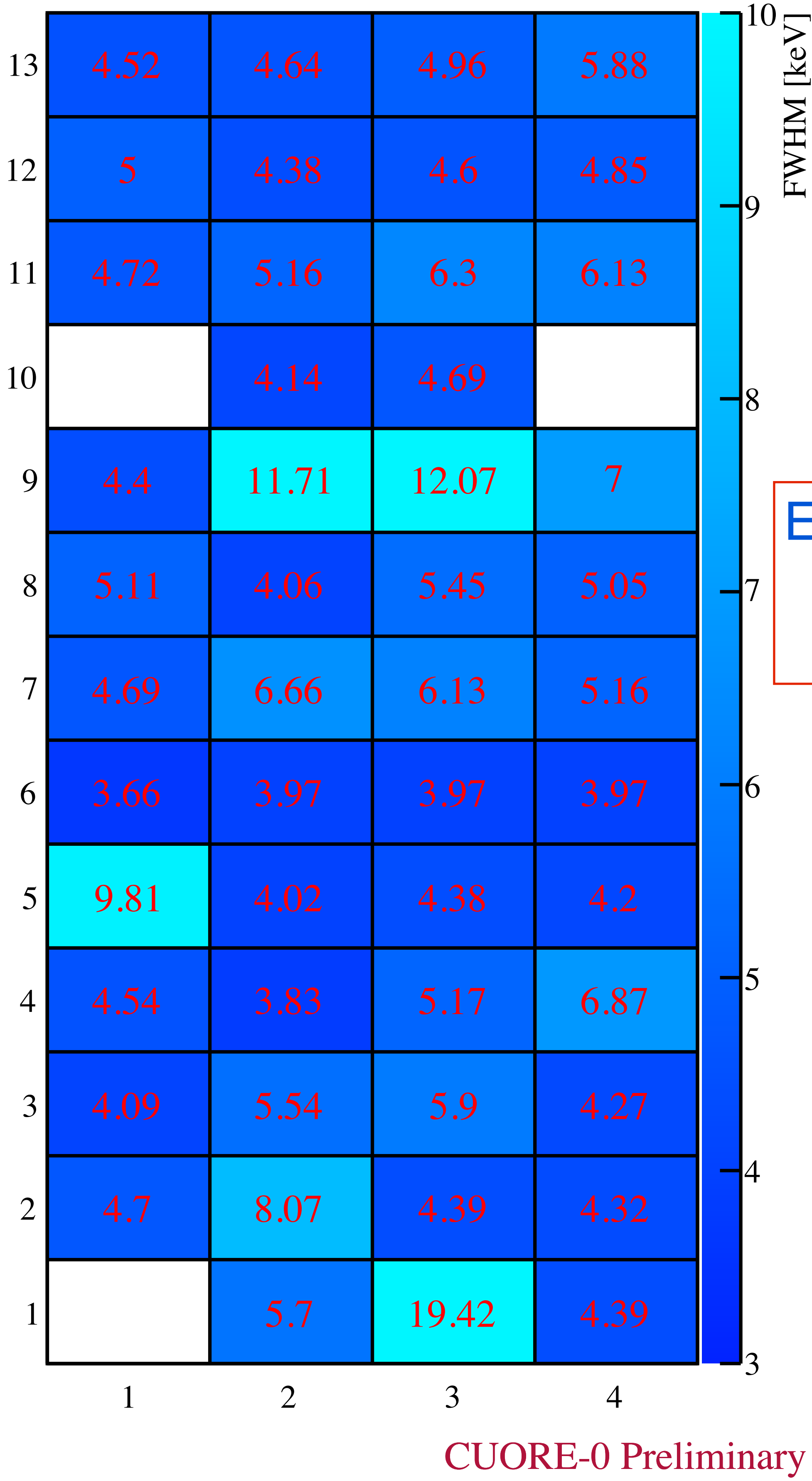
- ***CUORE goal reached!***



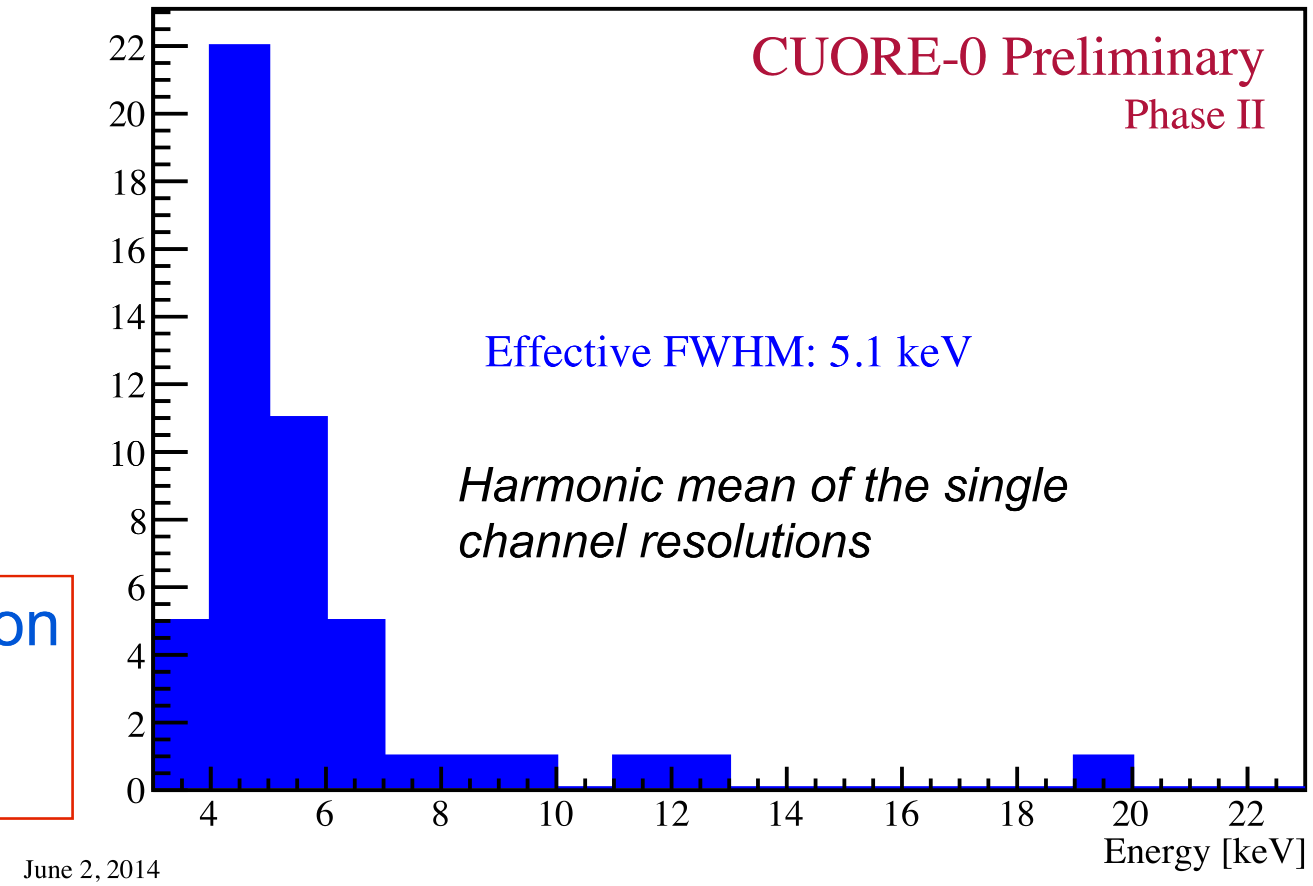


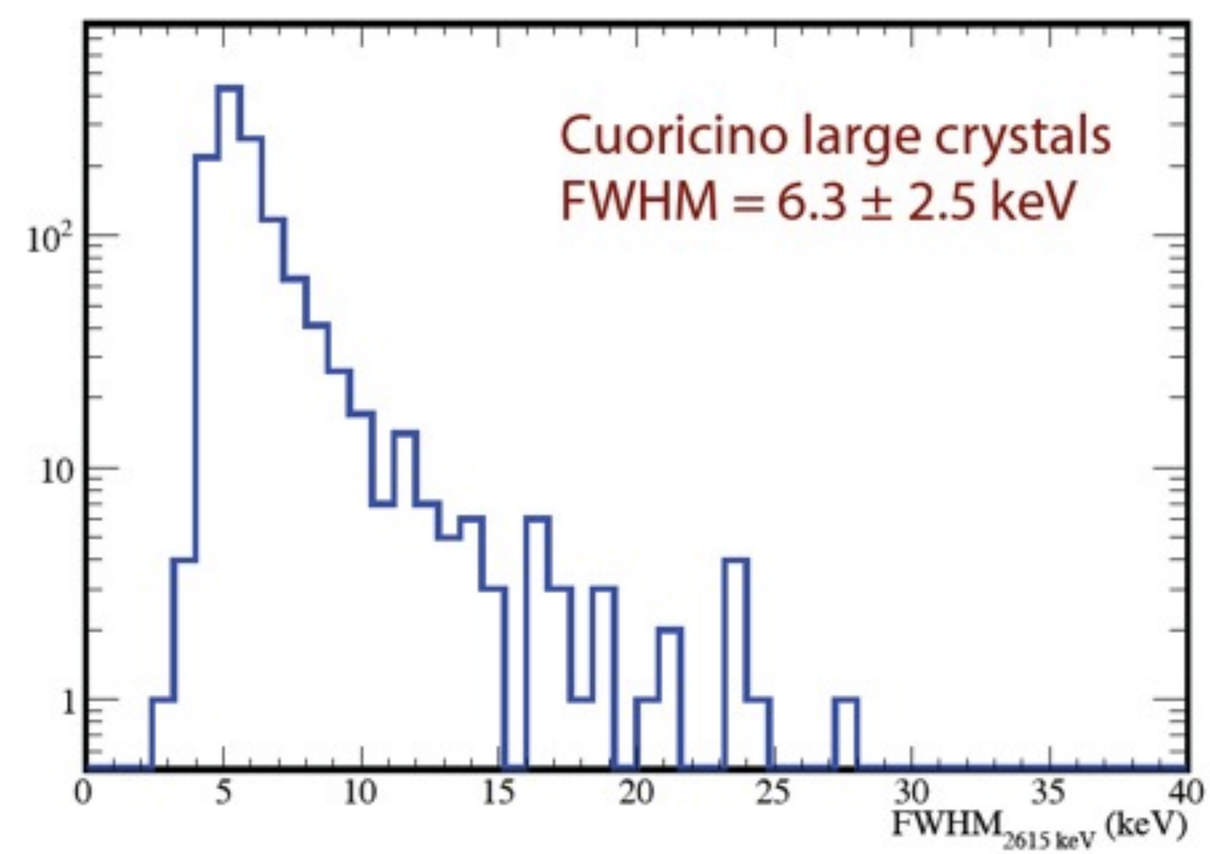


CUORE-0 energy resolution: phase II

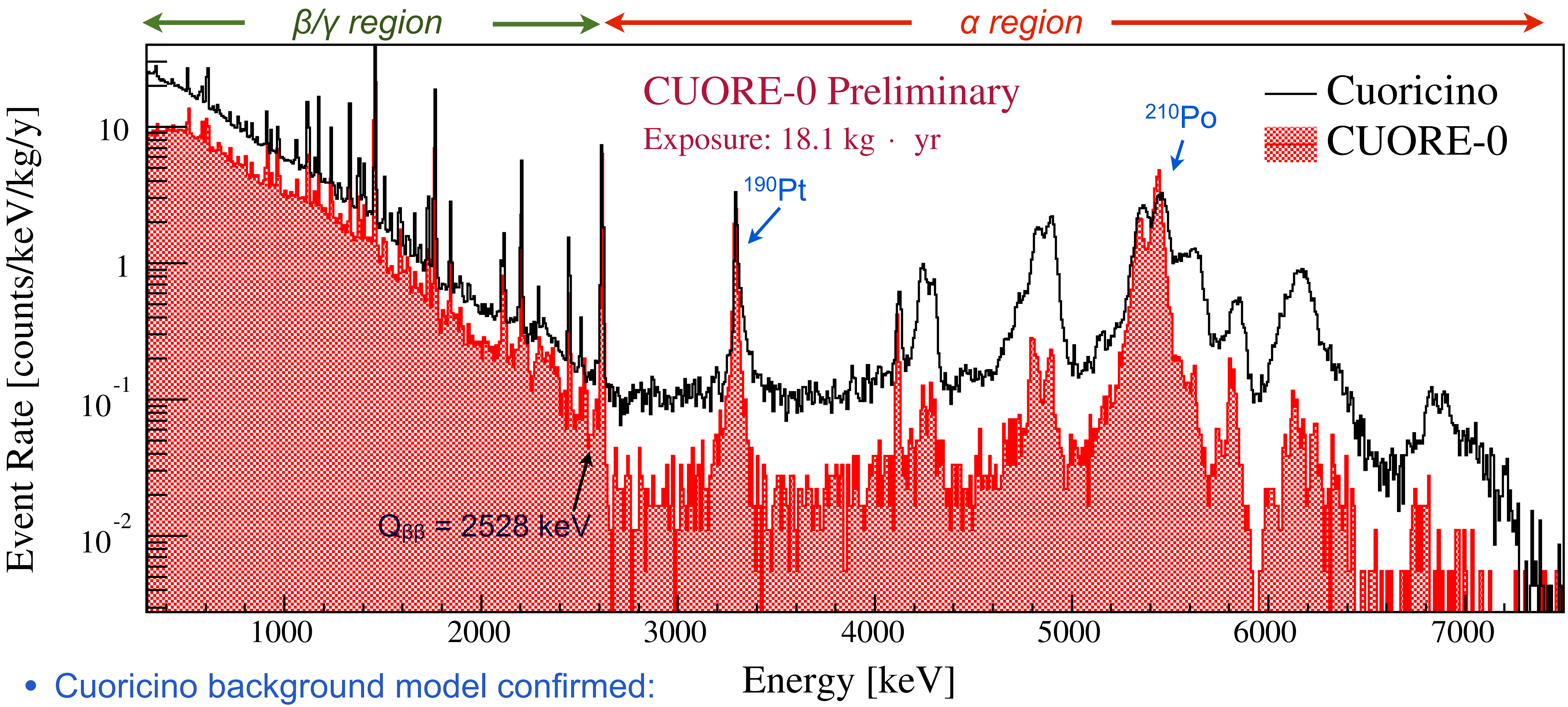


Energy resolution
@ 2615 keV
^{208}Tl γ line





CUORE-0 background

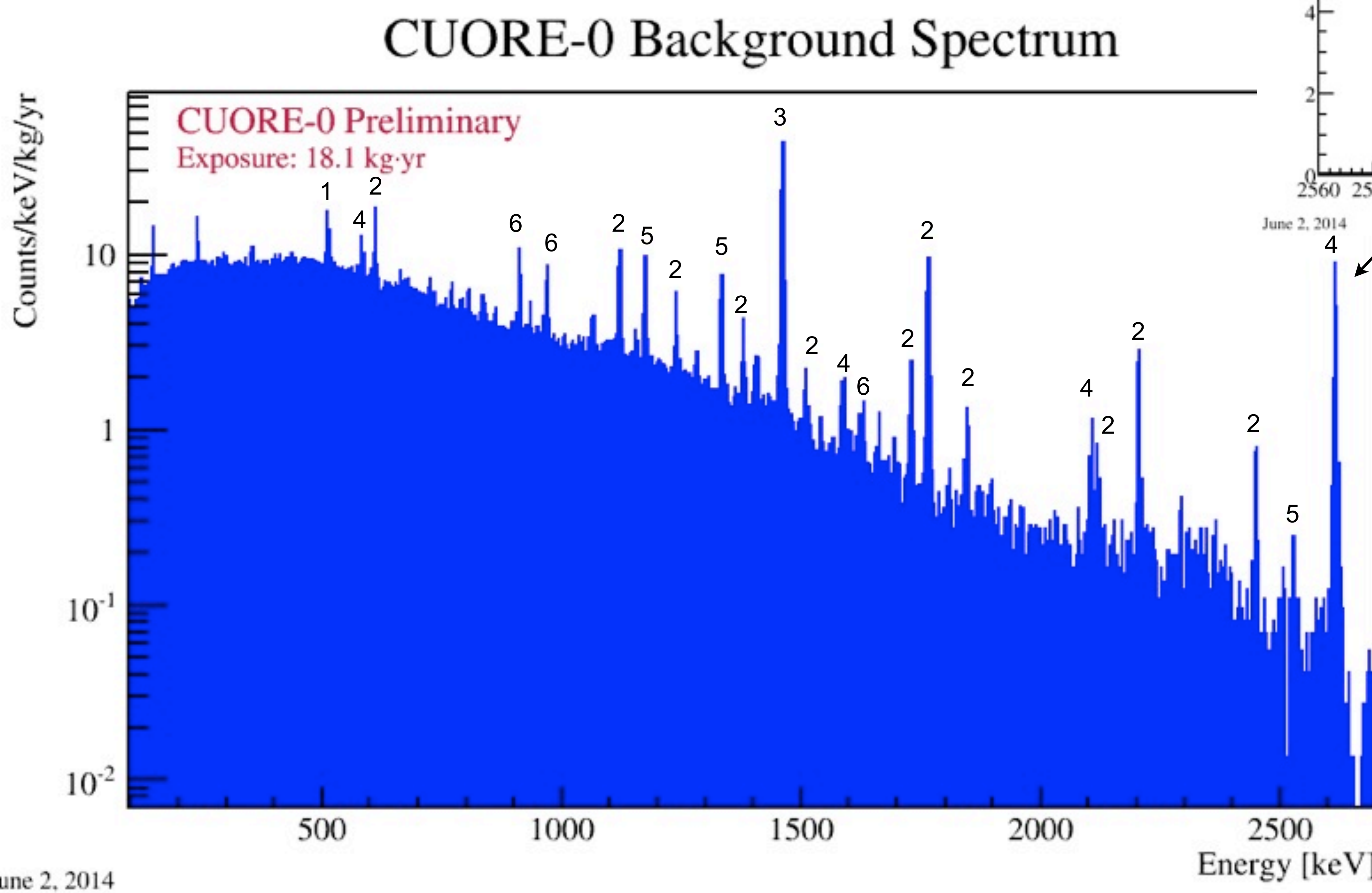


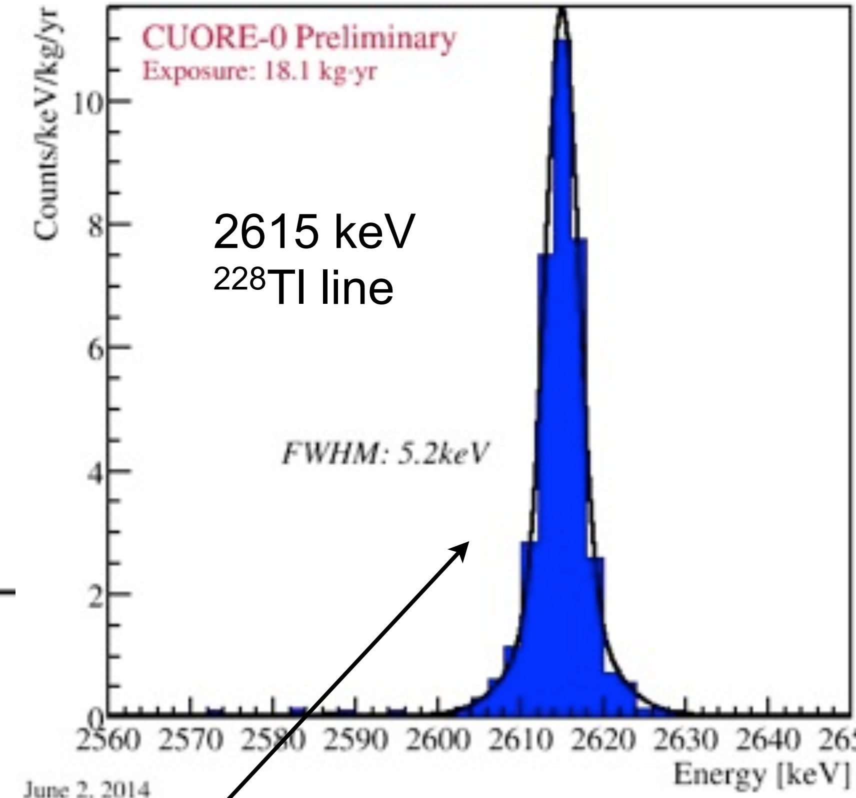
- Cuoricino background model confirmed:
  - environmental gamma's from material bulk contaminations
  - surface radioactive contaminations of close materials
- Evident reduction with respect to Cuoricino
  - factor of 6 for surface contaminations
  - factor ~2.5 in the ROI

	$0\nu\beta\beta$ region cnts/(keV kg y)	2700-3900 keV	ε(%)
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	**0.063 ± 0.006**	**0.020 ± 0.001**	78

CUORE-0 background: γ region

"Environmental" γ lines compatible with Cuoricino observations:
→ common cryogenic system



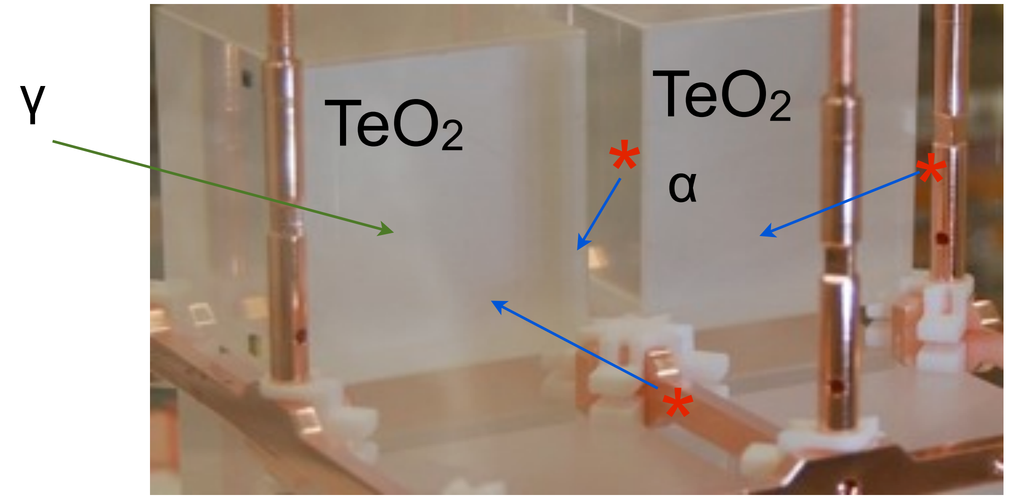


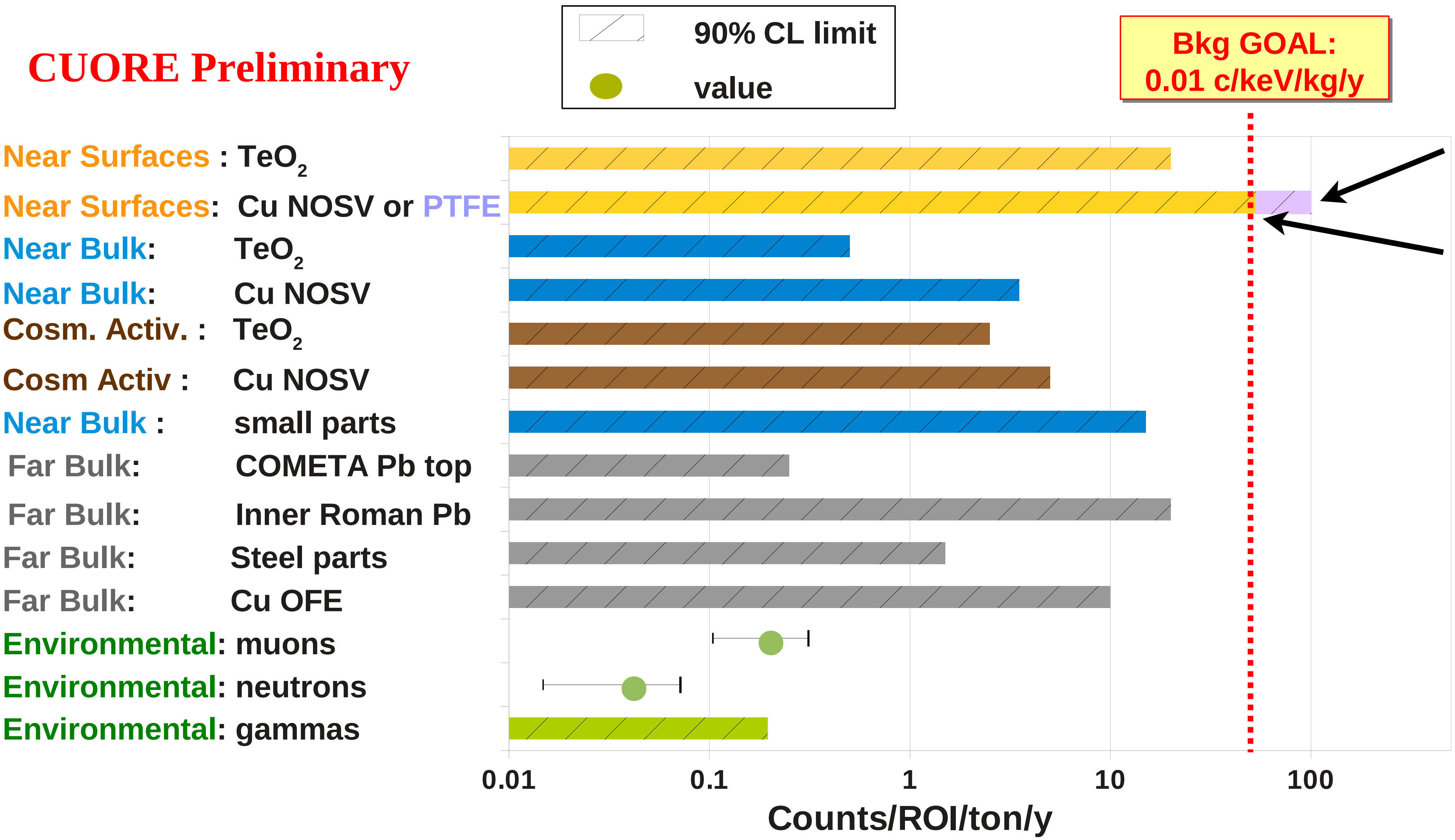
1. e^+e^- annihilation
2. ^{214}Bi
3. ^{40}K
4. ^{208}Tl
5. ^{60}Co
6. ^{228}Ac

CUORE background budget

CUORE background in ROI

- New cryostat with radio-pure materials → negligible gamma contributions
- More effective self-shielding → Copper surface background can be reduced below background goal.
- More effective anti-coincidence → negligible surface alpha from crystals

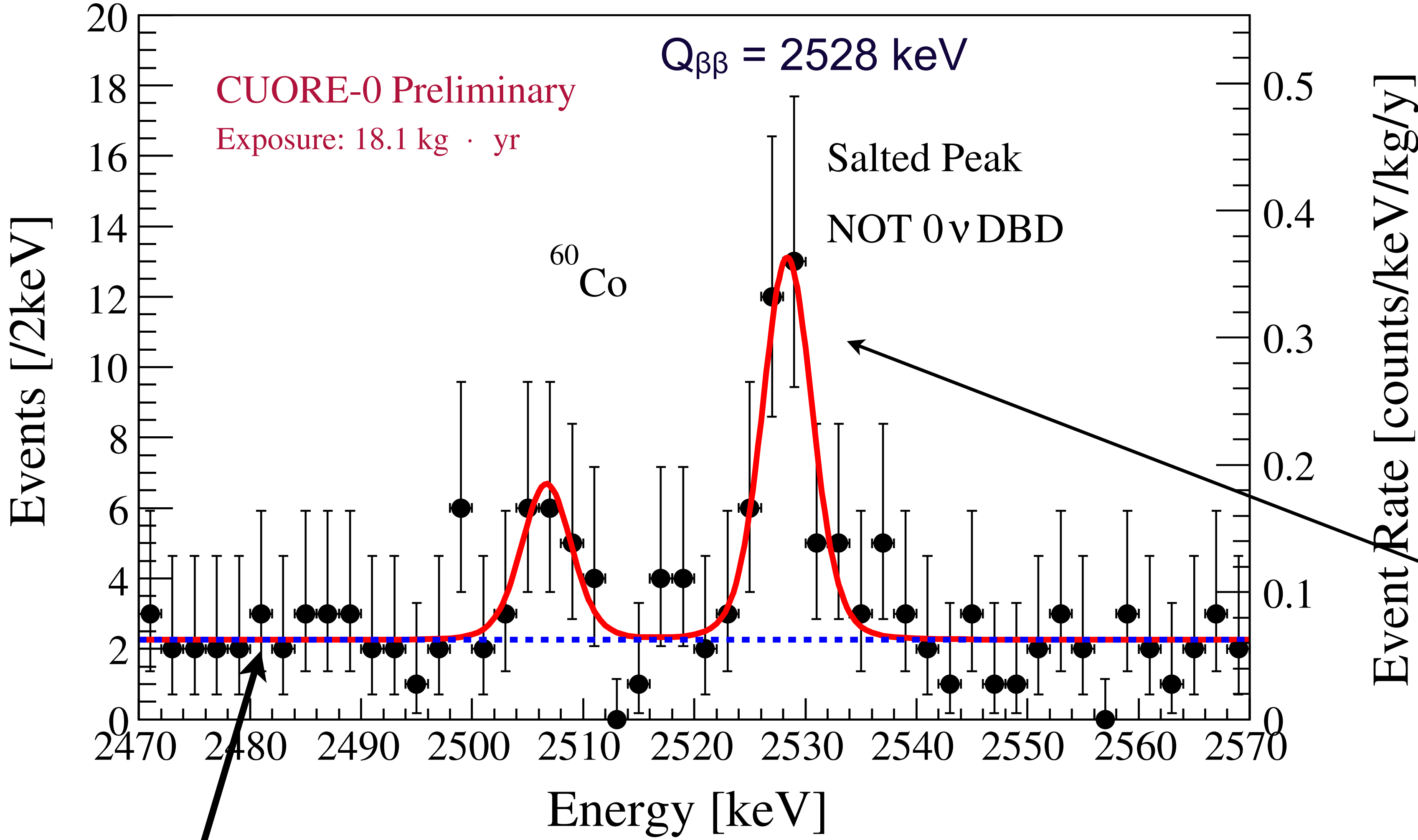


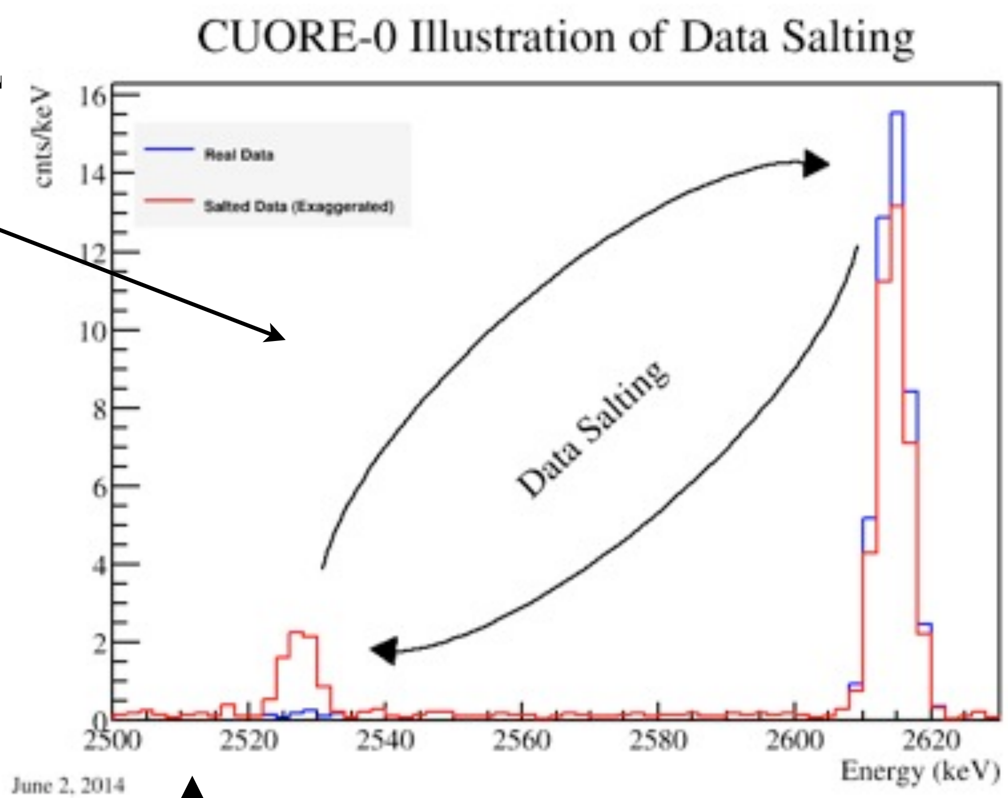


- **Conservative limits:** assume all contributions come from a single source

- **Full MC simulation** based on Background model and detailed description of the experimental setup

CUORE-0: ββ0ν ROI





Background consistent with Cuoricino model:

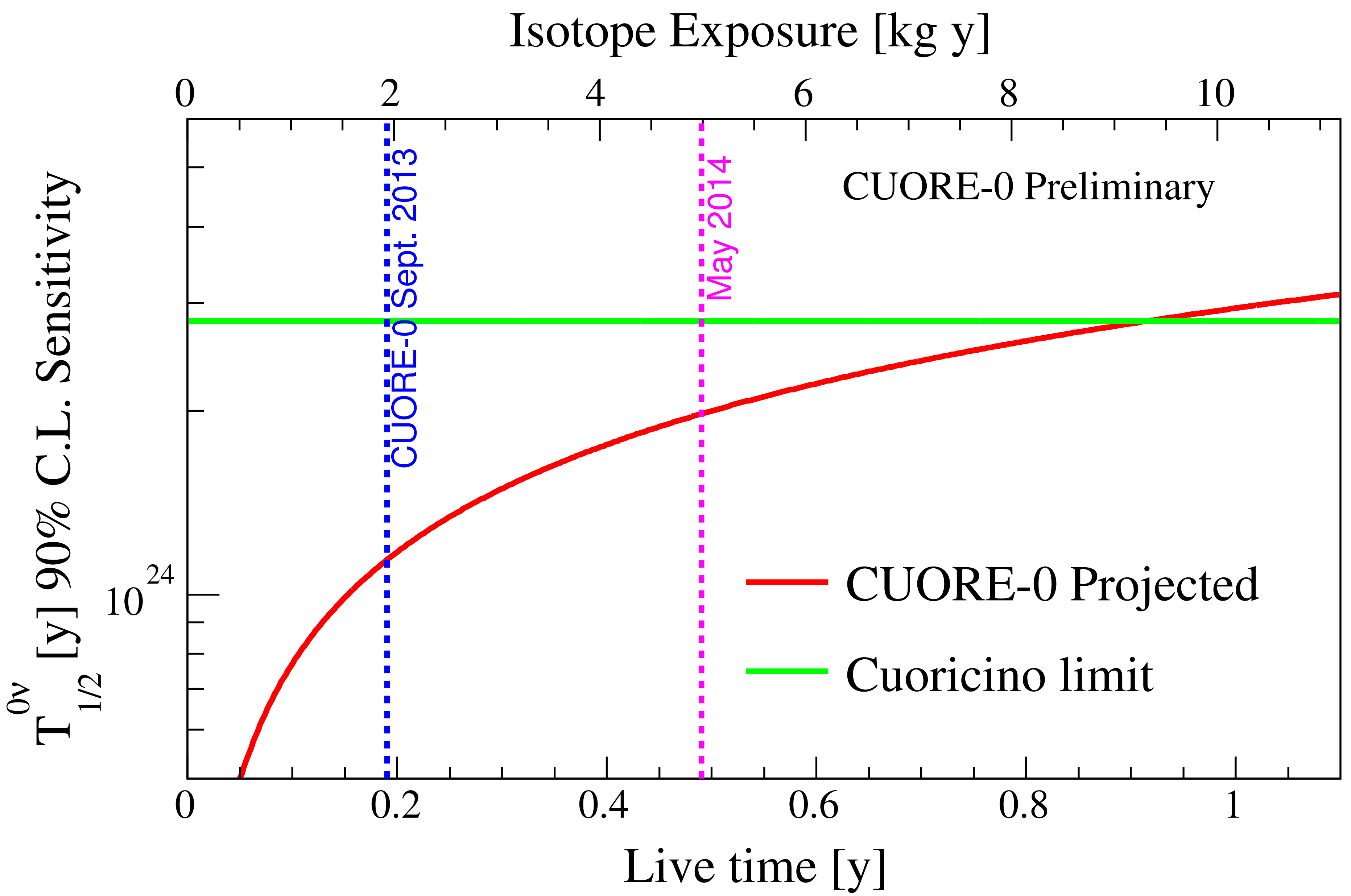
- dominated by ^{208}**Tl γ**'s from the environmental materials (mainly cryostat).

Unblinding: early 2015

Our blinding procedure produces an artificial peak in the ROI:

a small (blinded) fraction of the events within ±10 keV of the 2615 keV peak from ^{208}Tl is exchanged with the events within ±10 keV of the Q-value

CUORE-0



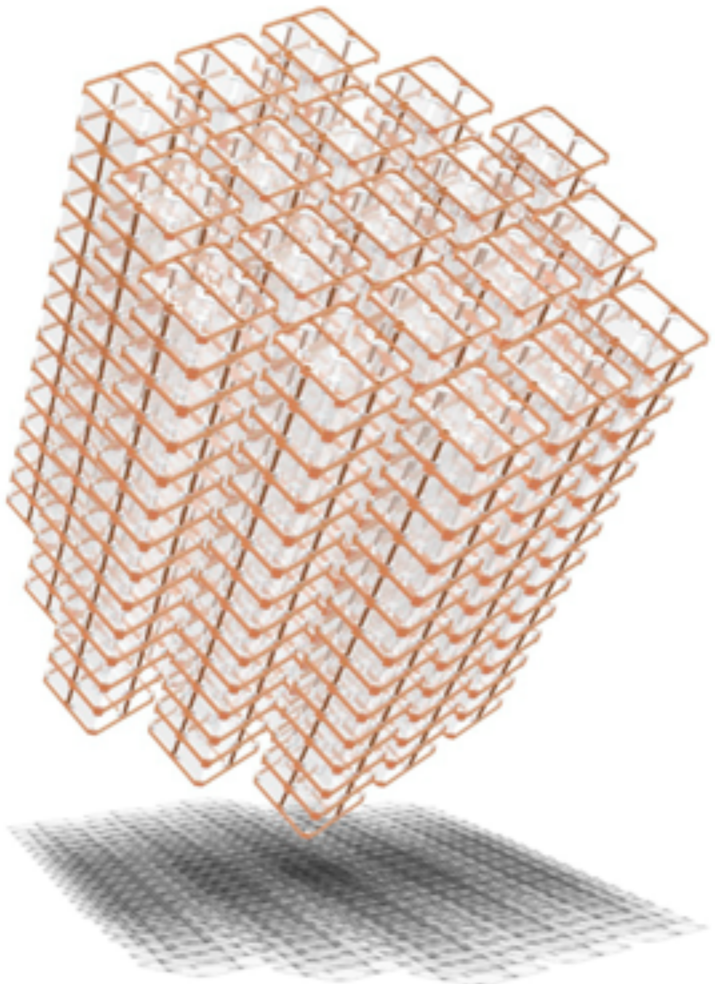
CUORE-0 expected to surpass Cuoricino sensitivity with ~1 year of livetime.

Energy resolution:
$\Delta E \sim 5.2$ keV FWHM @ 2615 keV
Background index (in the ββ ROI):
$b = 0.063 \pm 0.006$ cnts/(keV·kg·yr)

- Improvements to noise still in progress
- Pulse shape cuts are still being optimized

→ **CUORE-0 sensitivity may still improve in the future.**

Status of CUORE: the detector



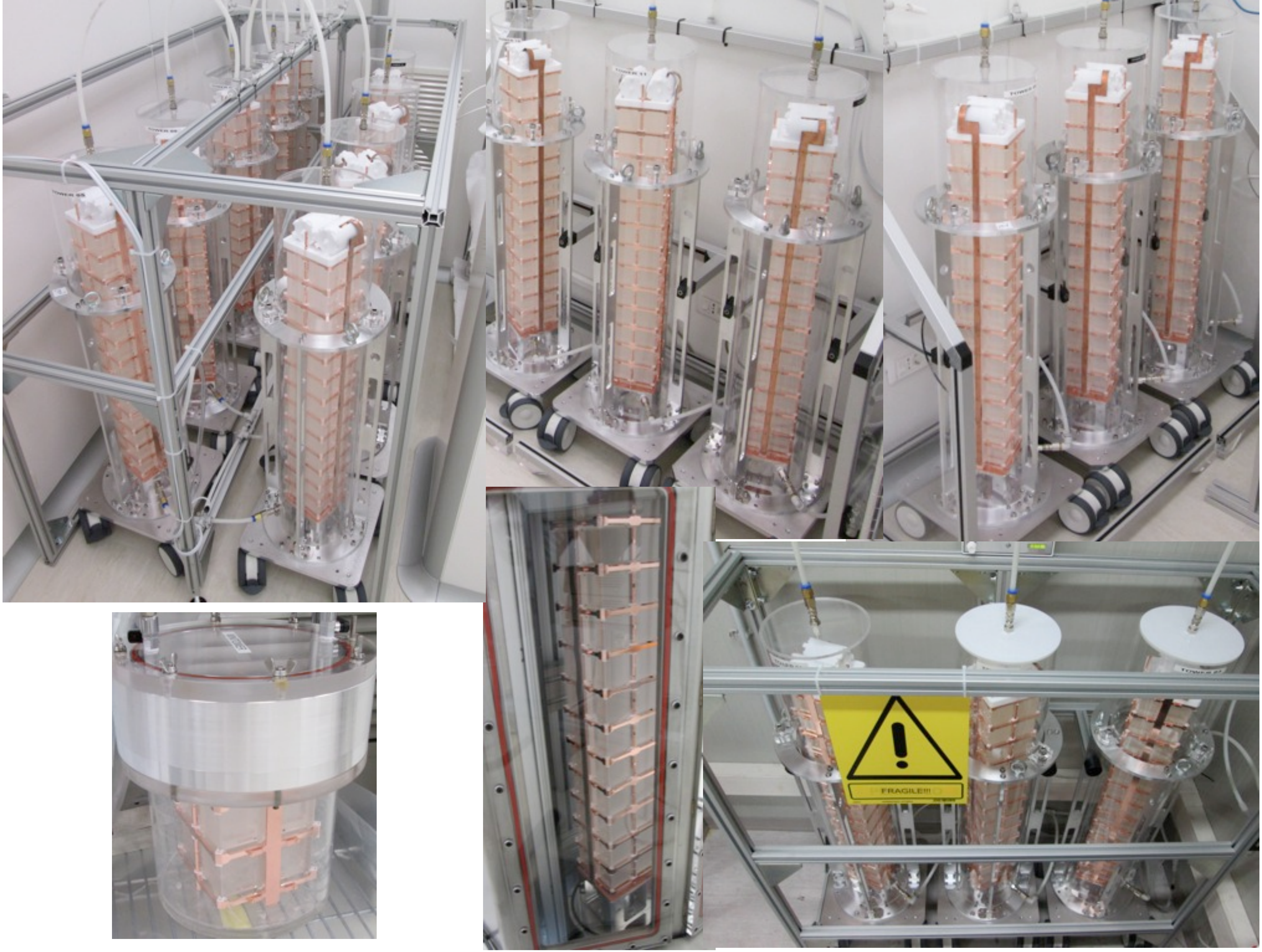
September 2011: tower assembly line commissioning complete
March 2012: CUORE-0 construction
February 2013: start of crystal gluing operations

Presently:

- **all 19 towers have been mechanically assembled** (Transformed ~10000 components into 19 ultra-clean towers)
- **18 fully instrumented and ready to mount towers**

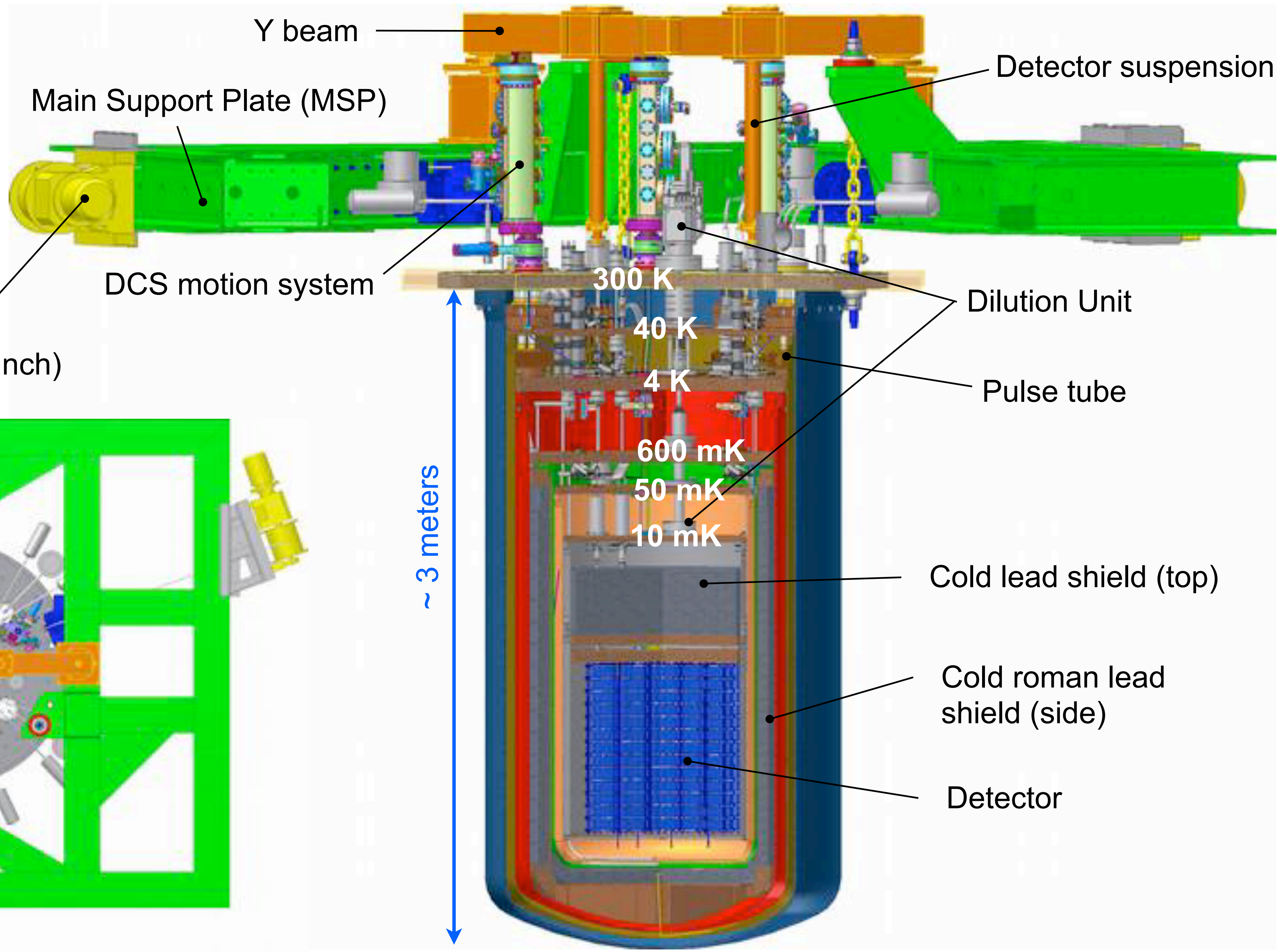
- **Tower assembly completion:**

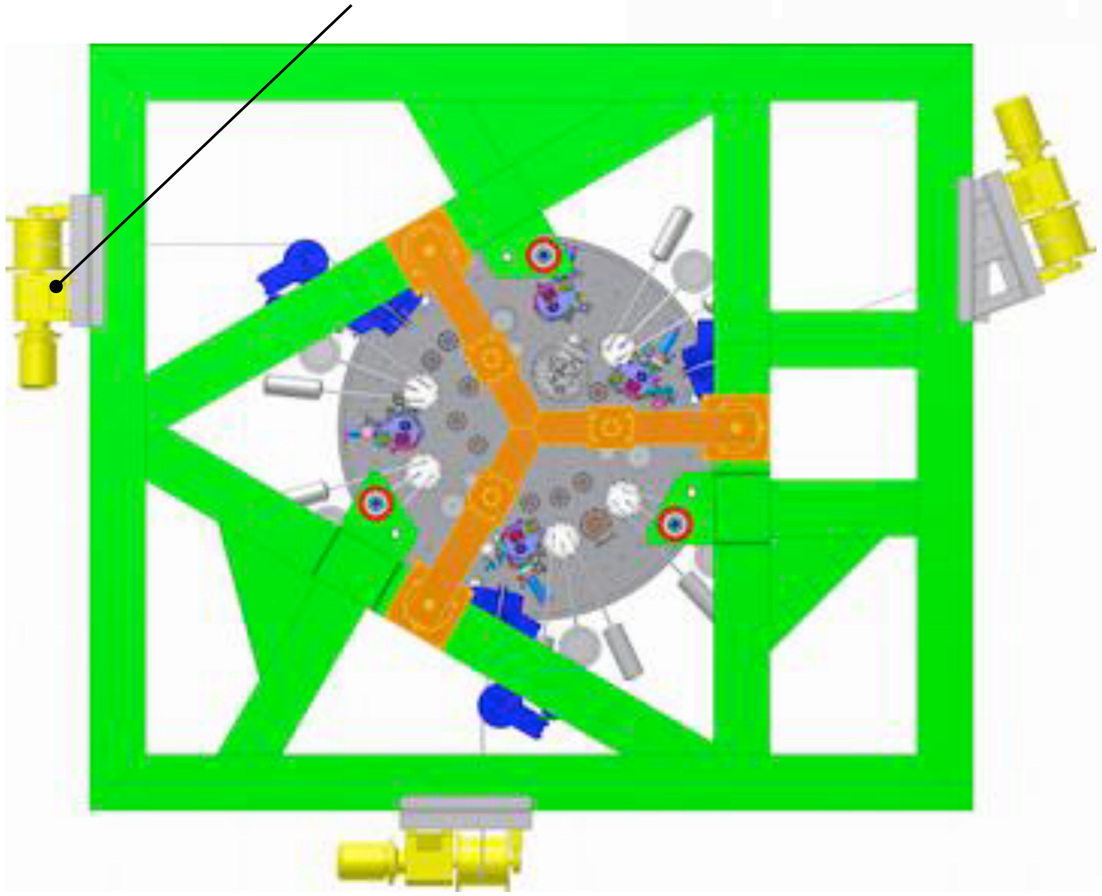
  June 2014 (very soon!)


FRAGILE!!!

Cryogenic set-up

Size:
300K Shield: ⌀1.7 x h 3.1
Weight:
Detector: ~1 ton
Pbshields: ~10 tons
Cu shields/flanges: ~8 tons





Sub-systems:

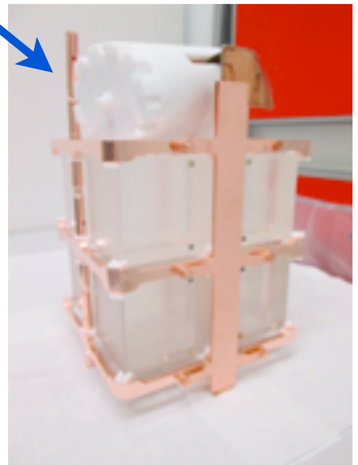
- Cryostat
- Pulse tubes
- Dilution unit
- Fast cooling system
- Platforms
- Suspensions
- Lifting system
- Wiring
- Low T shields
- Calibration system

Status of CUORE: cryogenics

Phased commissioning program

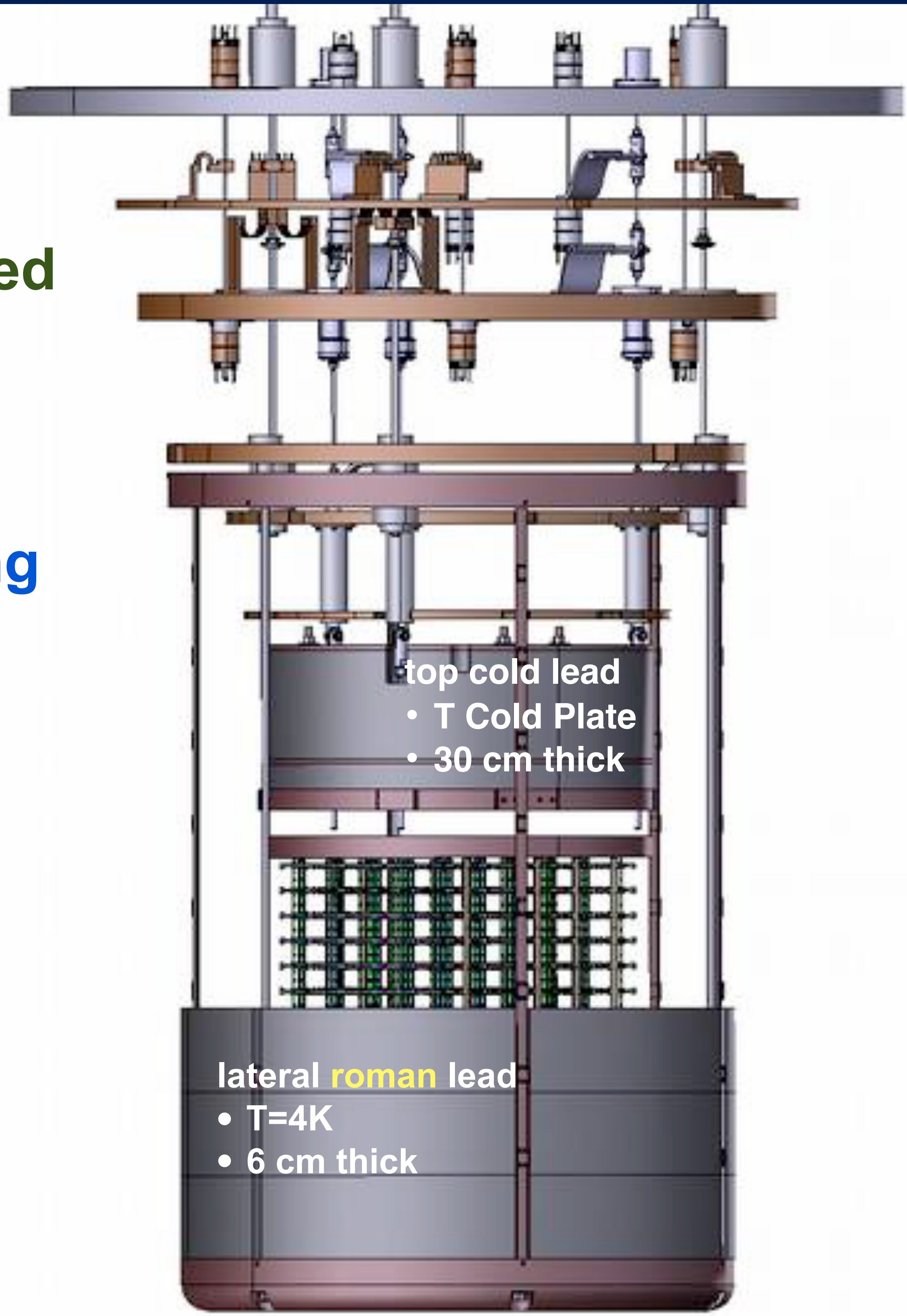
→ add complexity gradually

- **Phase I: 4 K subsystem → completed**
  - OVC and IVC vacuum tightness
  - Cooldown to 4K
- **Phase II: full system test → ongoing**
  - **cryogenic system fully assembled**
  - **first cool-downs with no additional load:**
    - ✳ **reached 14 mK**
    - ✳ **still ongoing**
  - **next steps:**
    - wiring system (and test detector)
    - Cold Pb shield + FCS
    - DCS + Suspensions
    - Towers support plate

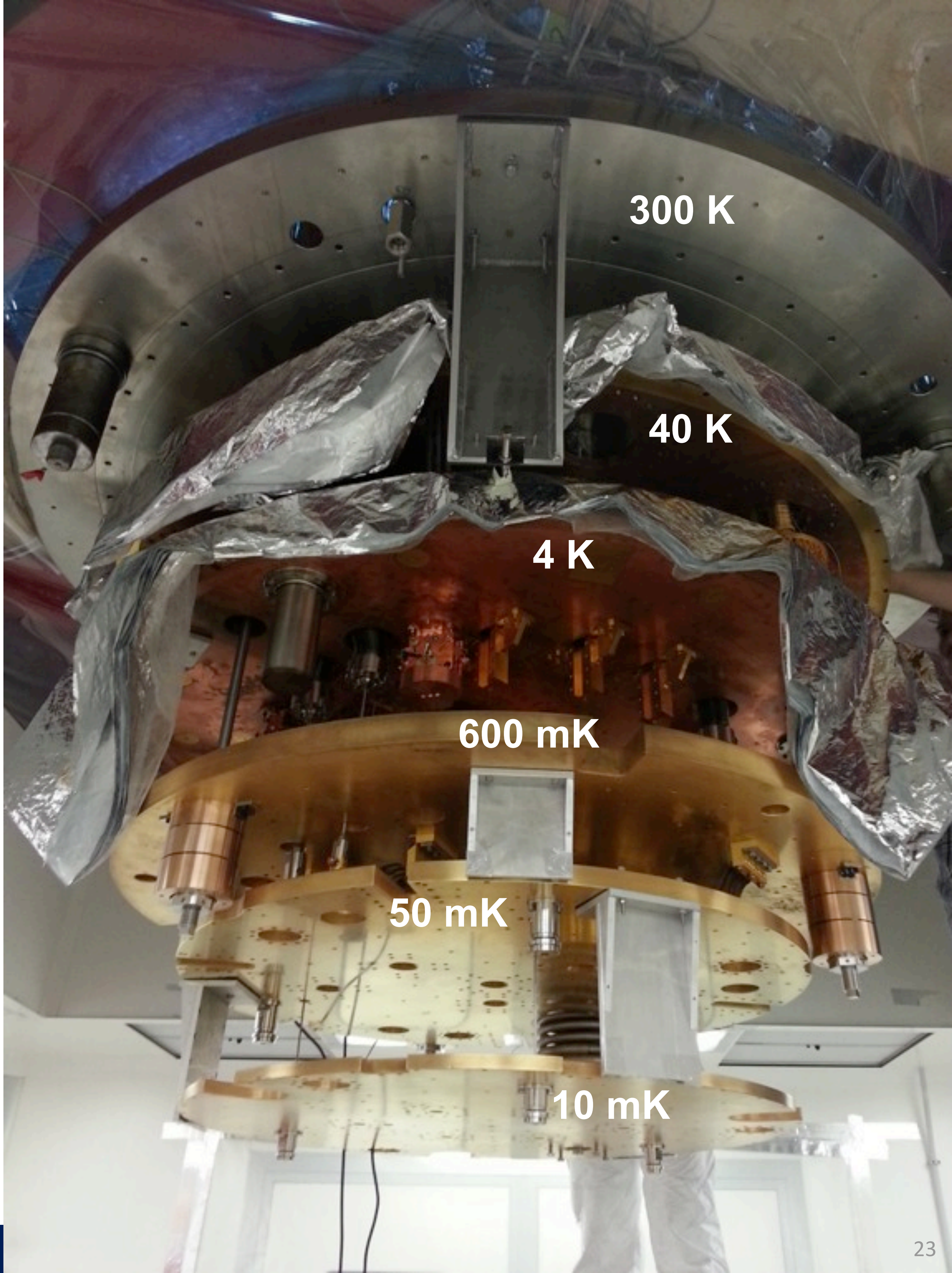


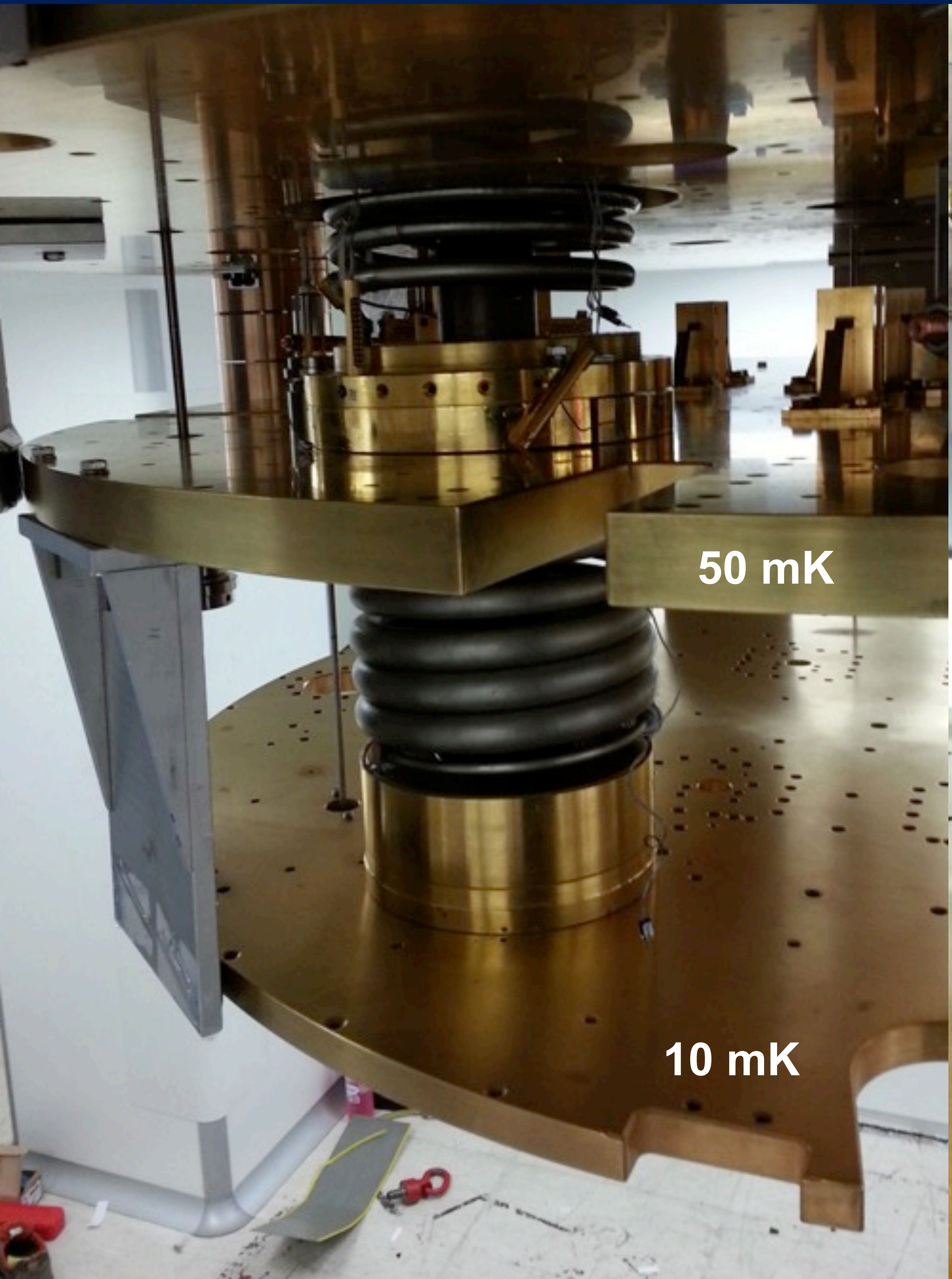
Expected completion:

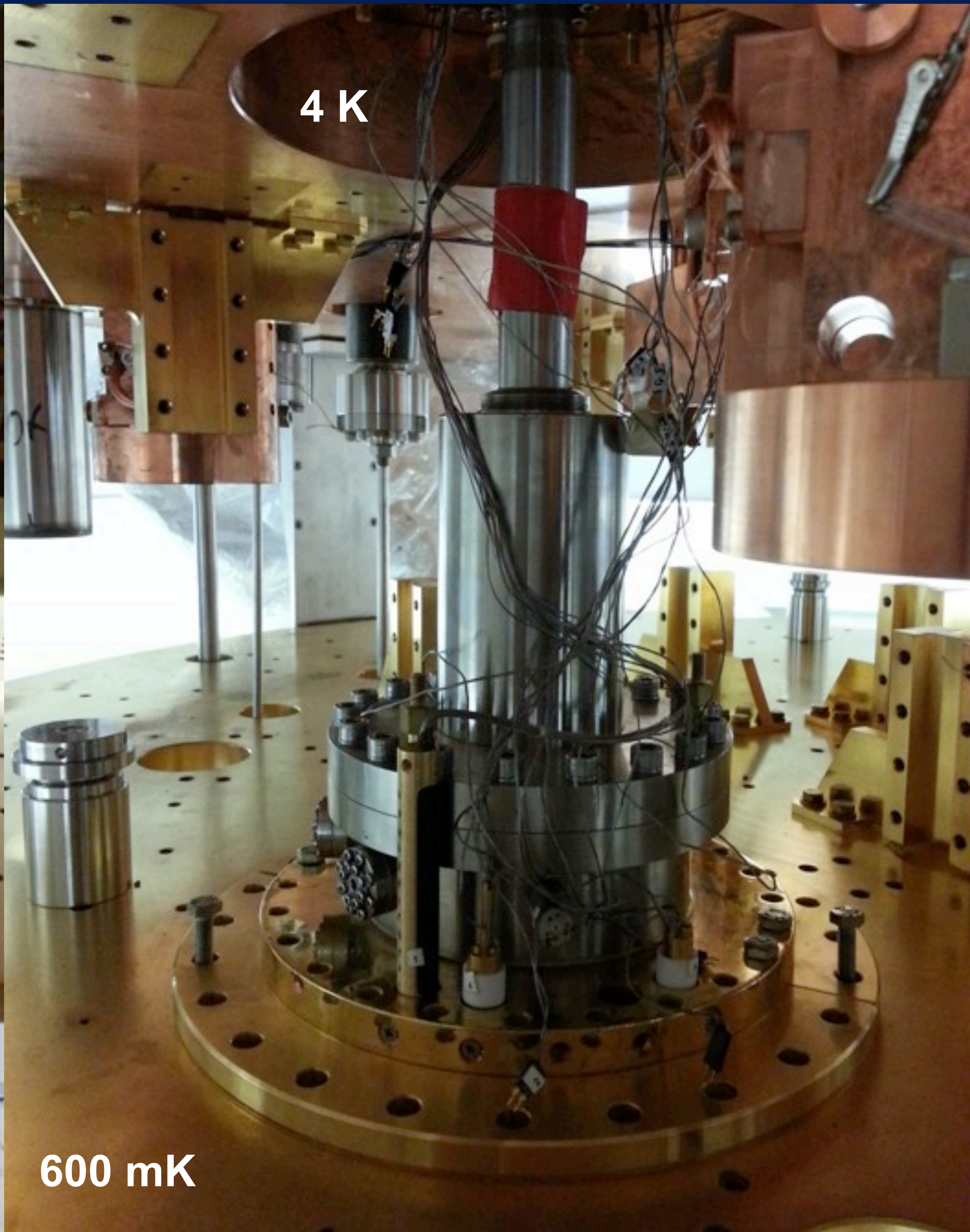
→ early 2015




300 K

40 K

300 K
40 K
4 K
600 mK
50 mK
10 mK


50 mK
10 mK


4 K
600 mK


300 K
~3 meters
10 mK
~1.4 meters
mock-up vessel

Status of CUORE

Moving to detector integration (installation into the cryostat)

- very delicate operation (towers exposed to air)
- protected area flushed with Rn-free air
- dedicated installation tools
- still copper cleaning
- detector interfaces
- detector cage (ultra-cleaning - detector grade)

Detector installation: spring 2015

In the meanwhile all the other systems are being completed and moved to LNGS for installation:

- DAQ
- Data analysis tools
- Faraday cage

CUORE data taking will start in summer 2015

CUORE posters:
- Calibration system: J.Cushman
- CUORE-0: L.Canonica
- Data monitoring: K.Han
- Sensitivity: K.Lim

Beyond CUORE

Primary goal: complete the effort to make CUORE fully operative

However many new ideas have already been proposed/developed to improve CUORE sensitivity.

R&D's programs recently gathered under a common aegis for a future CUORE upgrade

- common program to gather/share all possible informations
- aim at exploring the IH region with ton-size bolometric detector

CUORE operation is an indispensable step

- to demonstrate viability of a well performing ton-size detector in stable conditions
- to guarantee the needed infrastructure and experience
- to provide unique (high statistics) informations on background at 10^{-2} c/(keV kg y) scale

but it's important to profit of the large amount of new developments to prepare a future project

All existing R&D's are focused on background reduction

According to Cuoricino (and CUORE-0) background model α surface contributions are the most dangerous source:

- discriminate surface α/β interactions
- discriminate surface/bulk events

Relevant results already obtained at the single detector level (e.g. LUCIFER, LUMINEU, Cherenkov detection, etc.)

To reach a sensitivity larger than 10^{27}y it's essential to improve all relevant parameters

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \, t_{meas}}{bkg \cdot \Delta E}}$$

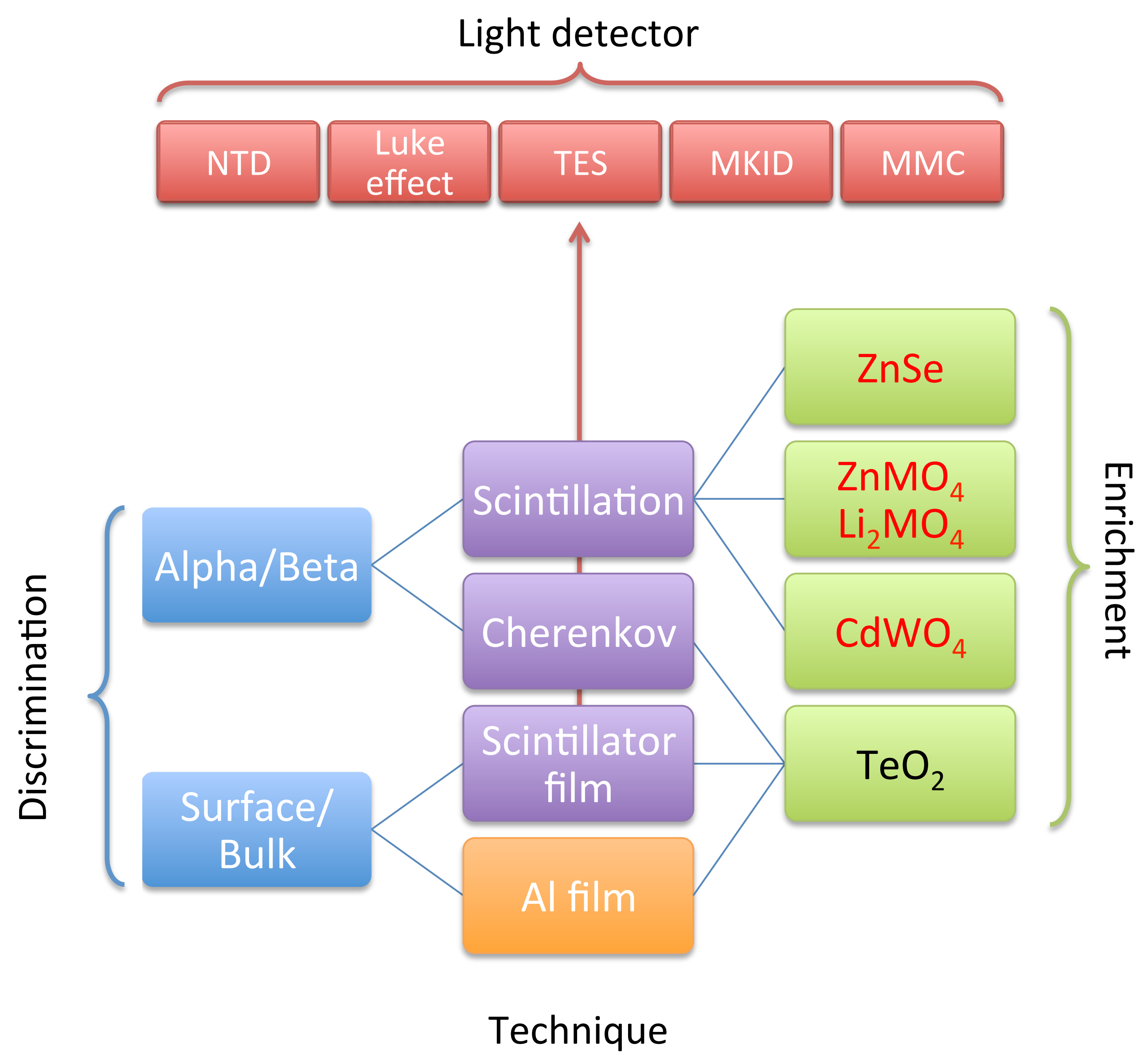
D.R.Artusa et al., arXiv:1404.4469 [hep-ex]

Beyond CUORE: R&D's directions

Bolometer R&D posters:
- CALDER: L. Cardani
- Cherenkov/TeO_2: N.Casali:
- LUCIFER: K.Schaeffner
- LUMINEU: A.Giuliani

Isotopic enrichment (80-90%):
- Scale CUORE design to O(1 ton) detector:
  - Relatively inexpensive isotopic enrichment of ^{130}Te ($17/g)
  - 718 kg of ^{130}Te in the same volume as CUORE (988 crystals)
  - A factor of 3 increase in isotope mass
- A must for isotopes other than ^{130}Te

Active background suppression to abate background in ROI:
- active alpha rejection:
  - scintillating bolometers: ZnSe, etc.
  - Cherenkov effect (on TeO_2)
- active surface event rejection
  - scintillating film
- passive surface event rejection
  - pulse shape discrimination through non-equilibrium phonons
- almost all the R&D require a powerful bolometric light detector
  - TES, MKID, Luke amplification, NTD



Other relevant aspects:
- Cosmic rays
  - ⟶ Materials activation
  - ⟶ Underground laboratory
- Environmental contributions
  - ⟶ Material selection, shields

Conclusions

CUORE-0

- CUORE-0 is taking data. It confirms the Cuoricino background model and demonstrates that an energy resolution $\lesssim$5 keV is achievable. It is a competitive DBD experiment in its own right
- The performance of the system has improved after the long fall maintenance
- We are optimizing analysis tools

CUORE

- Tower assembly to be completed this month: all the 19 towers have been assembled and 18 are fully instrumented.
- The commissioning of the cryogenic system is the greatest challenge: first cooldowns to base temperature are ongoing.
- End of the commissioning expected in spring 2015 followed by towers installation
- CUORE remains a major DBD experiment, with a potential to be the leader in this field through the end of the decade
- Start of operations in 2015

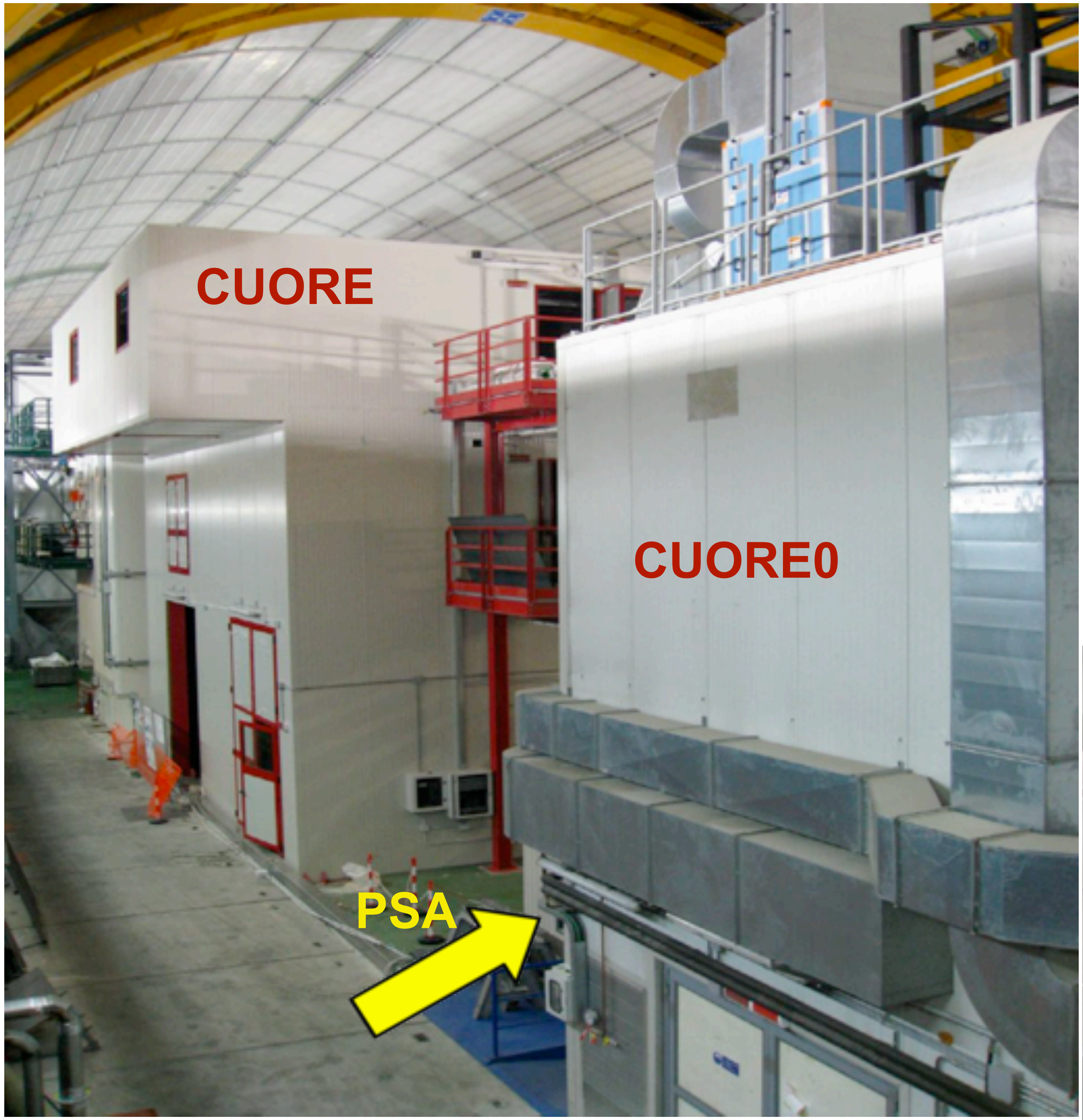
$\longrightarrow$ **CUORE results at Neutrino 2016 in London**

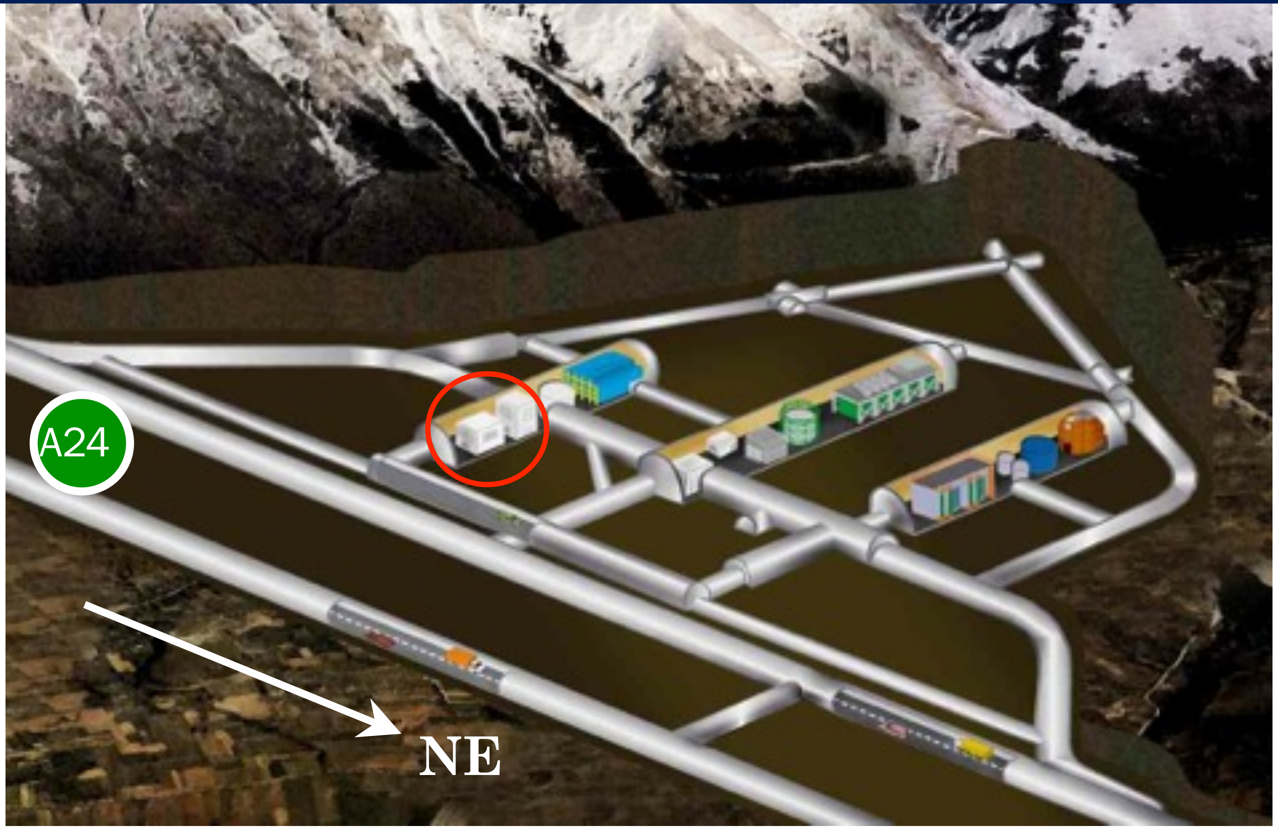
- Next-generation bolometric experiment has the potential to convincingly discover, or rule out, $0\nu\beta\beta$ in the entire Inverted Hierarchy region
- Aim for a technology choice for the next-generation experiment and a proposal on the timescale of 2016

$\longrightarrow$ **We are open to anyone who wants to contribute to this effort**

Backup slides

PSA (Part Storage Area)



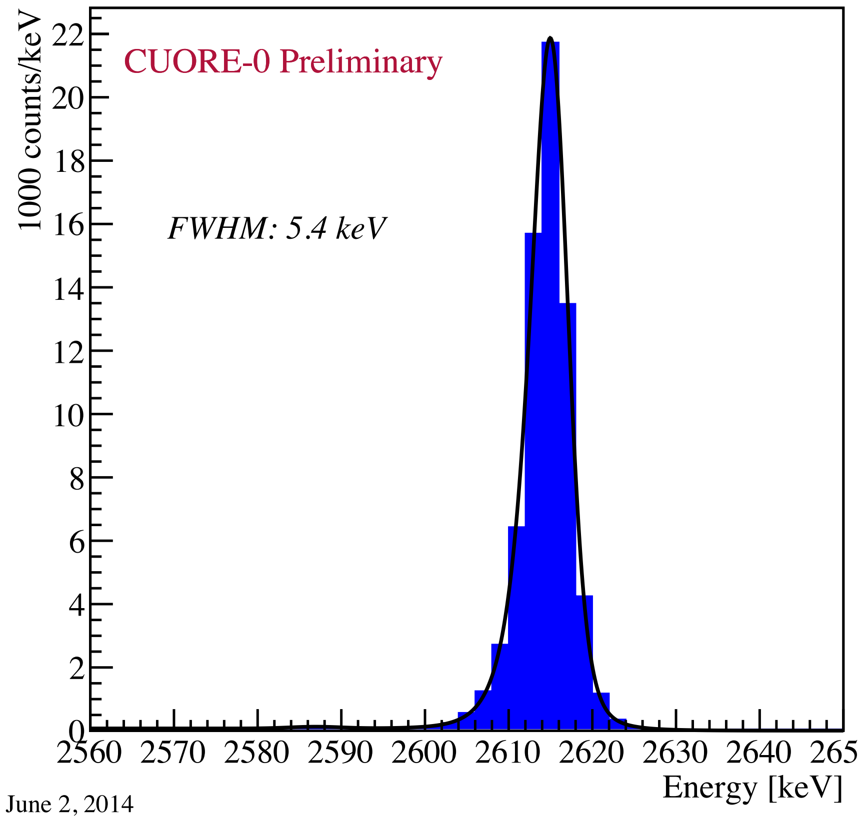


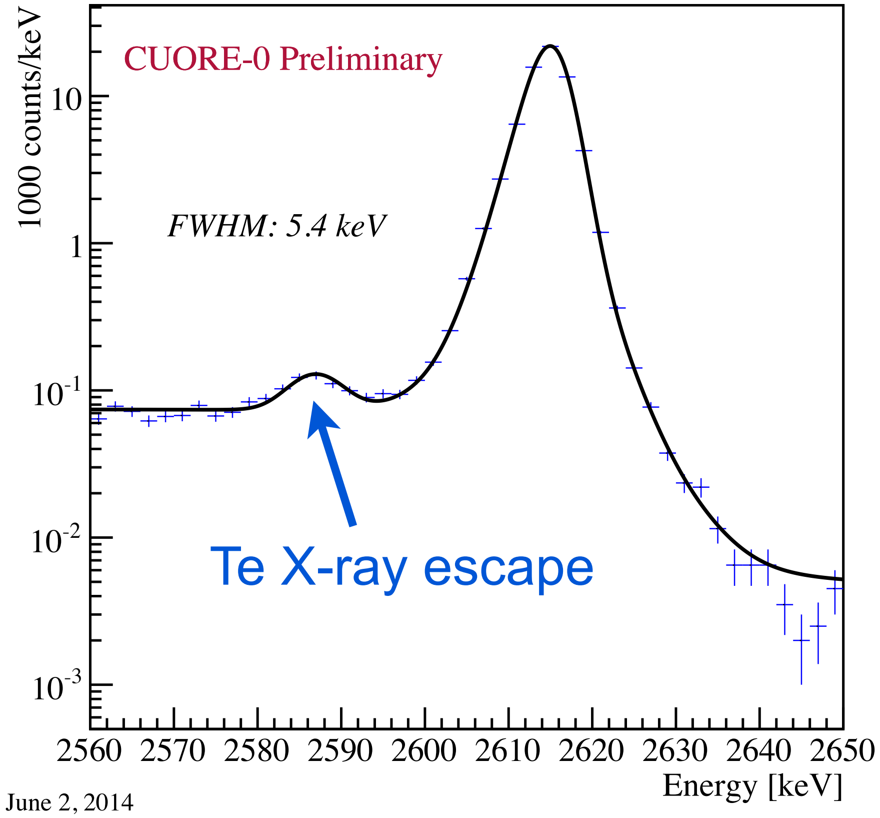
- Boxes of glued crystals are put inside N_2-fluxed PSA storage cabinets while awaiting for assembly

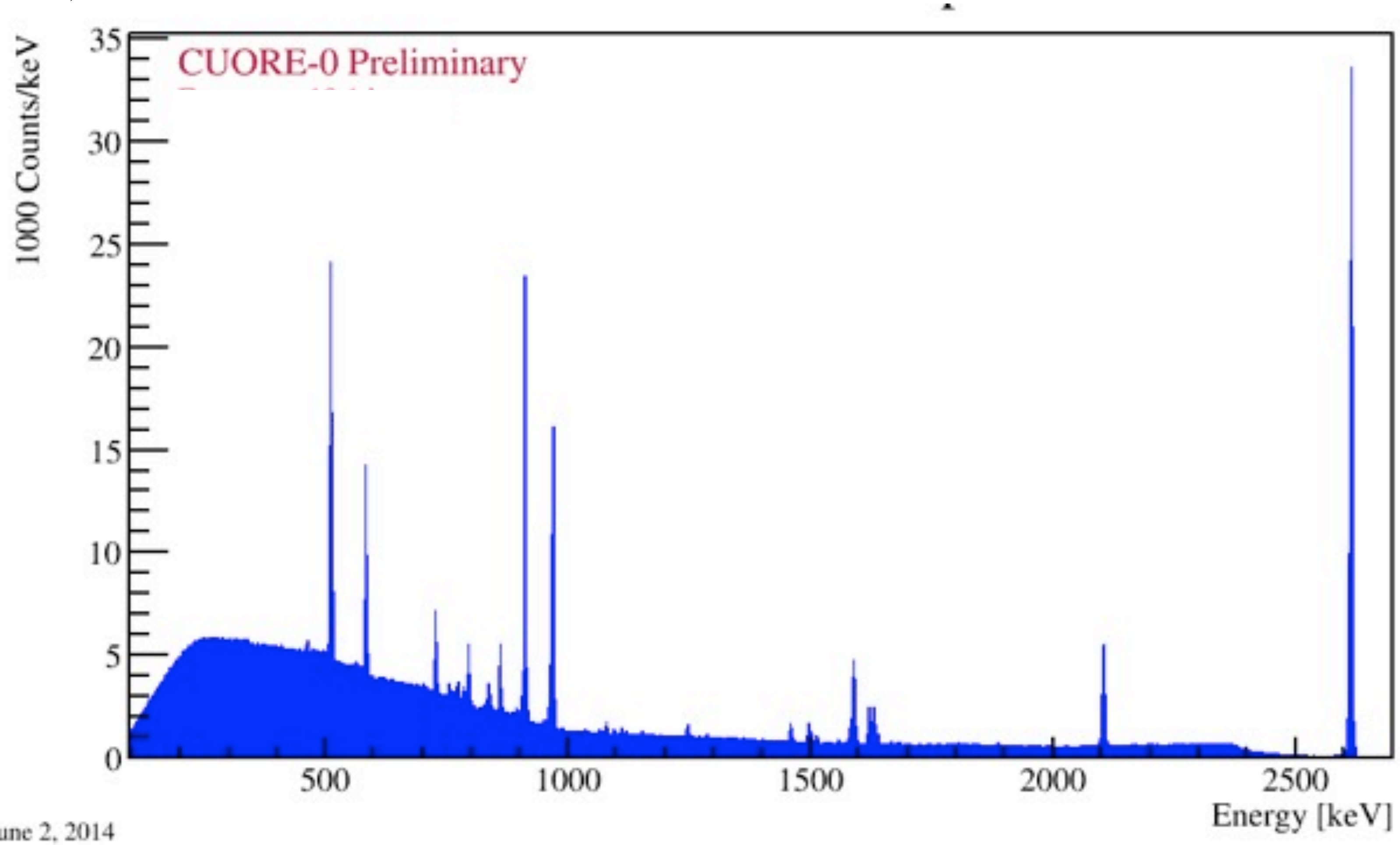
Some R&D’s references

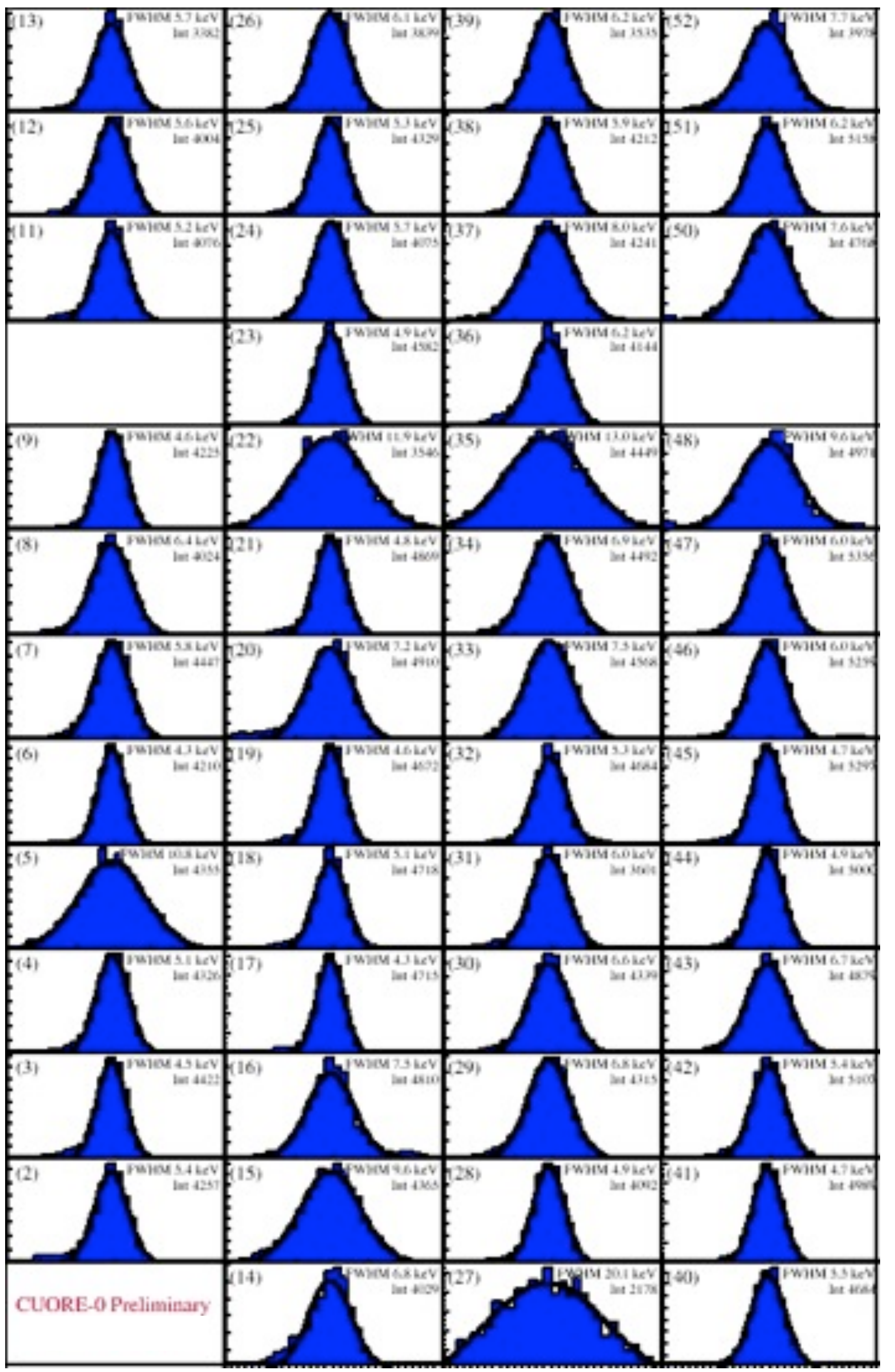
- *A.Alessandrello et al., Physics Letters B 420 (1998) 109*
- *C. Arnaboldi et al., Astropart.Phys. 34 (pp)2011) 797; arXiv:1011.5415 [nucl-ex]*
- *C. Arnaboldi et al., Astropart.Phys. 34 (2011) 344; arXiv:1006.2721 [nucl-ex]*
- *C. Arnaboldi et al., Astropart.Phys. 34 (2010) 143; arXiv:1005.1239 [nucl-ex]*
- *D.R. Artusa et al., arXiv:1404.4469 [nucl-ex]*
- *J.W. Beeman et al., Phys. Lett. B 710 (2012) 318*
- *J.W. Beeman et al., Astropart. Phys. 35 (2012) 813*
- *J.W. Beeman et al., Eur. Phys. J. C 72 (2012) 2142*
- *J.W. Beeman et al. JINST 8 (2013) P05021.*
- *J.W. Beeman et al., Adv. High En. Phys. 2013 (2013) 237973*
- *L. Bergé et al., JINST, in the press (preliminary version in arXiv:1312.3515v1 [physics.ins-det])*
- *C. Bucci, P.Gorla, W.Seidel arXiv:1103.5296*
- *L.Canonica, et al., NIM A 732 286-289 (2013)*
- *L. Cardani et al., JINST 8 (2013) P10002*
- *L. Cardani et al., arXiv:1312.4680 [nucl-ex] ; J. Nucl. Phys. G, in the press*
- *N. Casali et al., arXiv:1403.5528*
- *D.M. Chernyak et al., Eur. Phys. J. C 72(2012)1*
- *D.M. Chernyak et al., Nucl. Instr. Meth. A 729(2013)856*
- *M. Loidl et al., J. Low Temp. Phys., in the press*
- *C. Nones et al., J. Low Temp. Phys. 167(2012) 1029*
- *E. Olivieri et al., J. Low Temp. Phys. 151(2008)884*
- *T. Tabarelli de Fatis et al., Eur.Phys.J. C 65 (2010) 359*

CUORE-0 energy resolution: Phase I+II

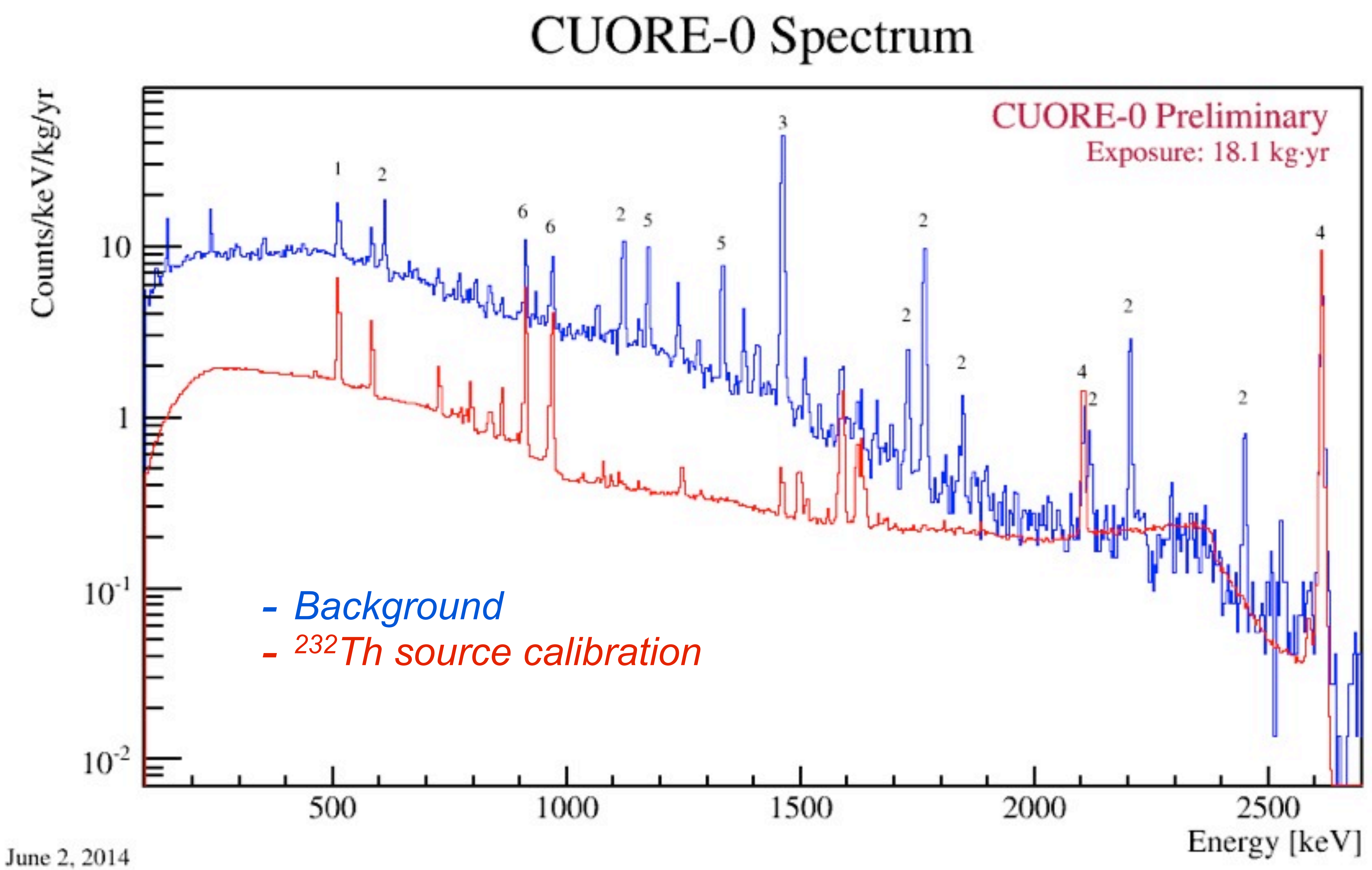






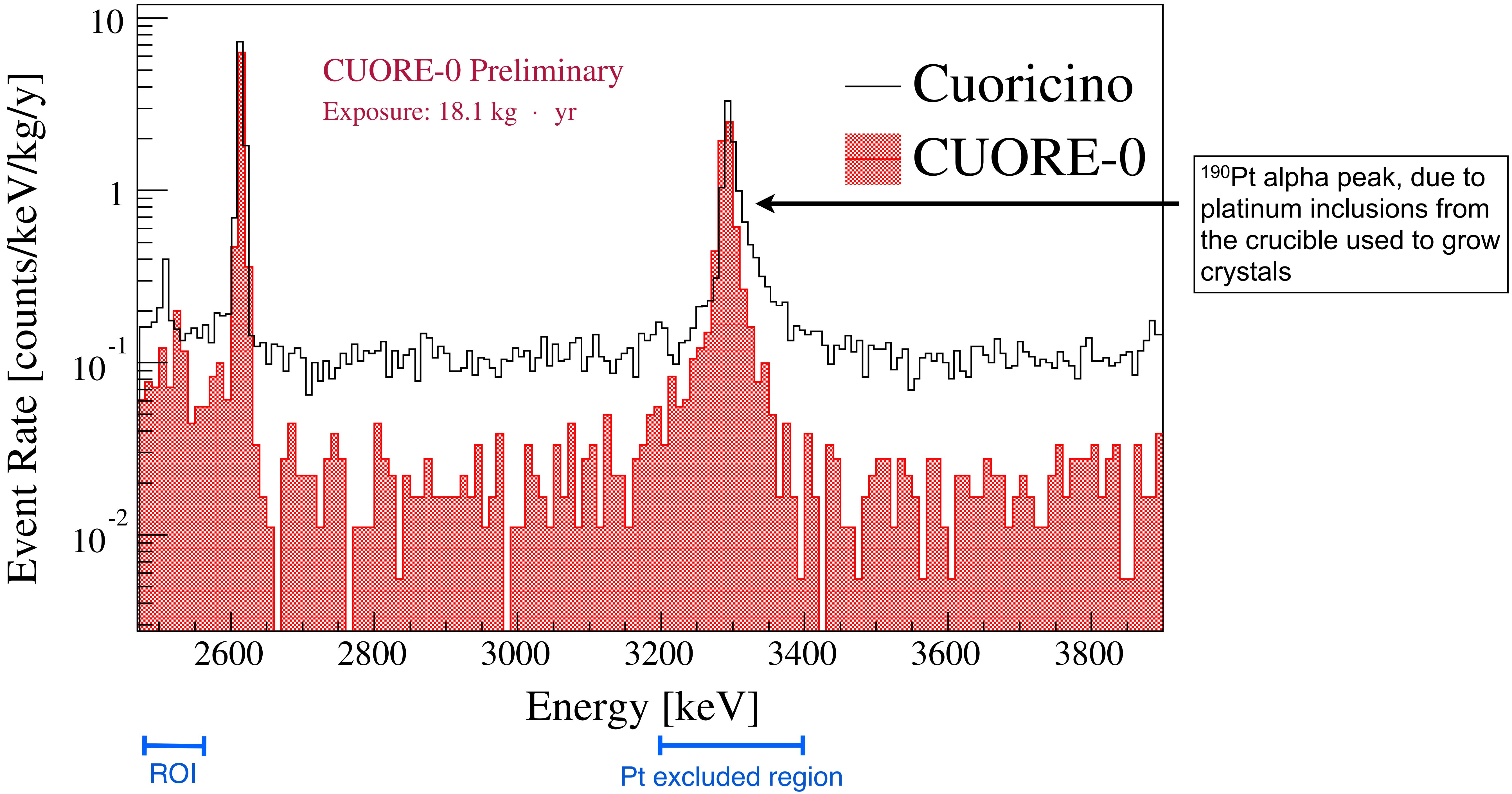


CUORE-0 background



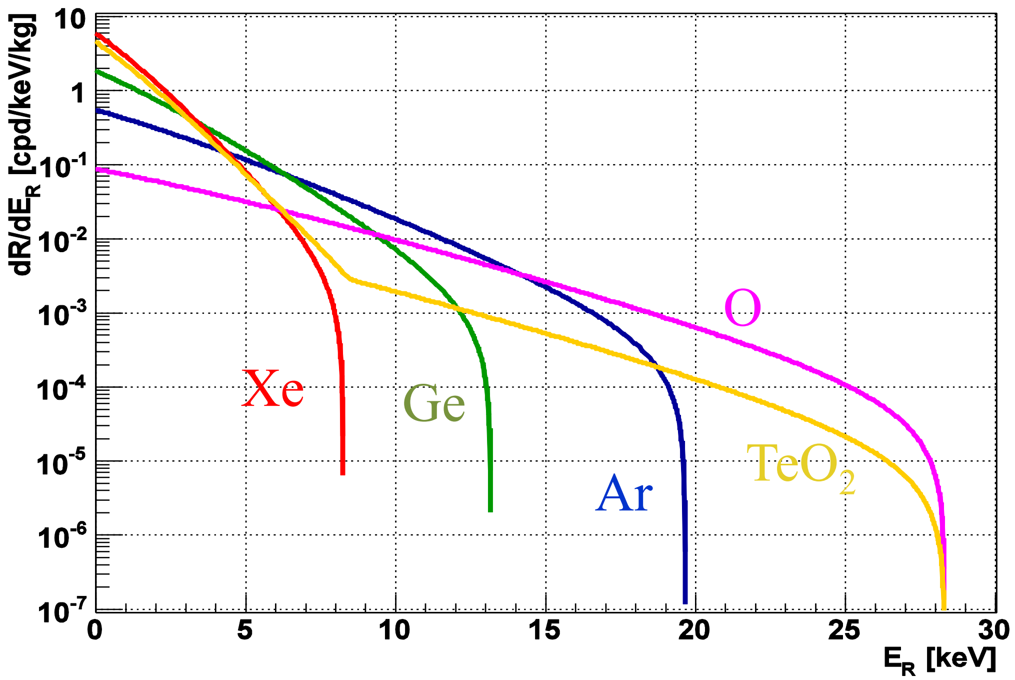
1. e^+e^- annihilation
2. ^{214}Bi
3. ^{40}K
4. ^{208}Tl
5. ^{60}Co
6. ^{228}Ac

CUORE-0 background: α region

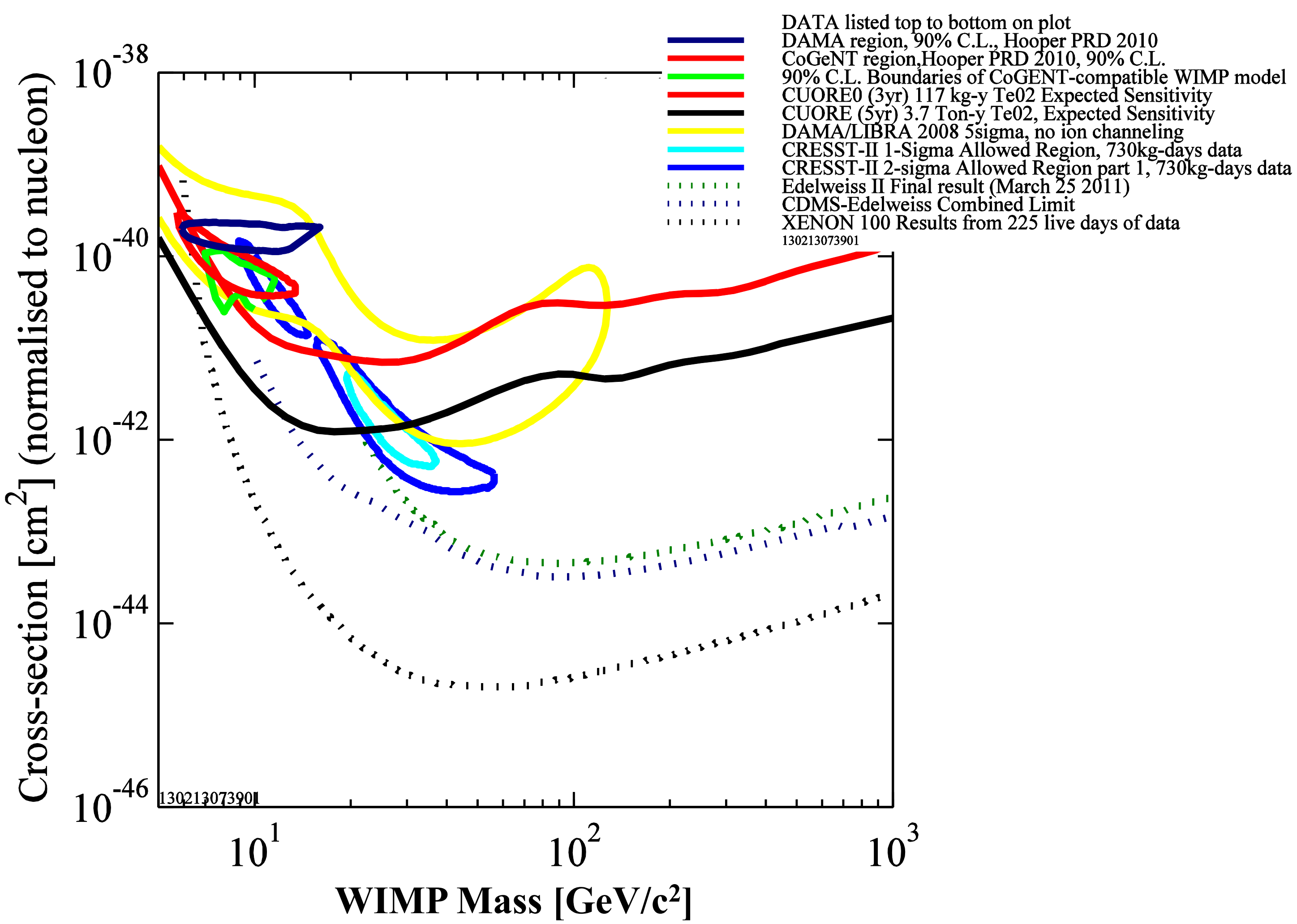


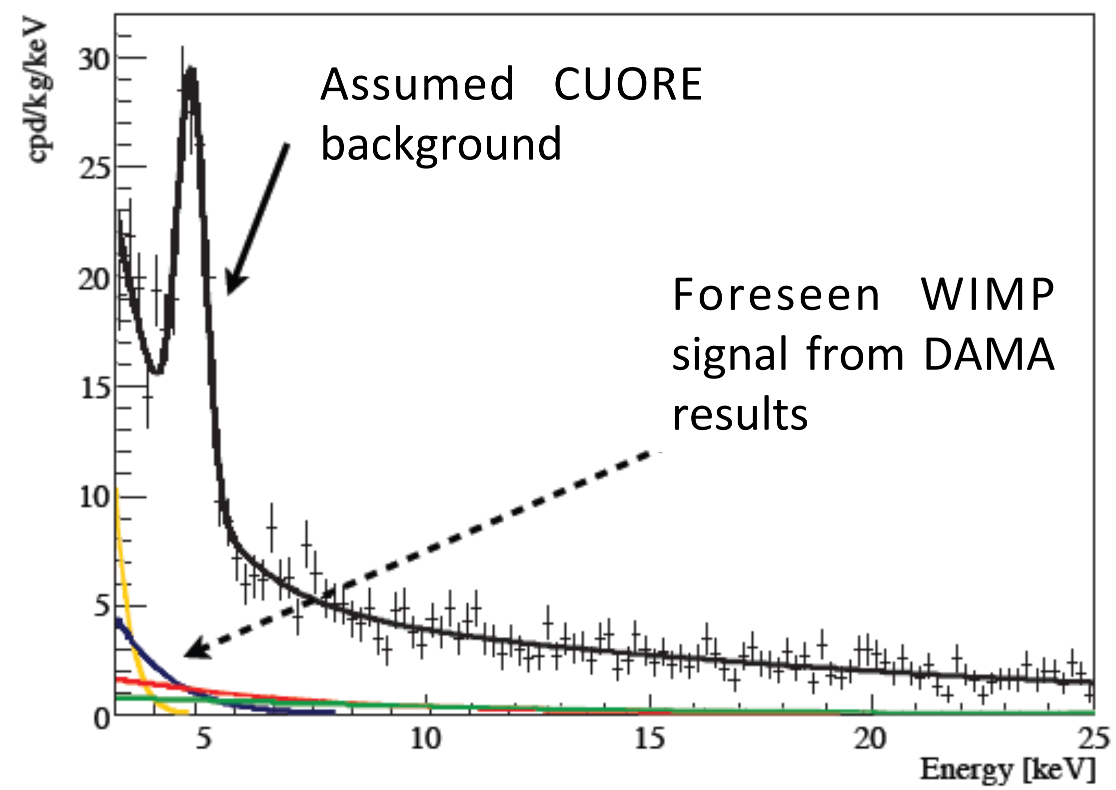
- The background in the alpha-dominated region (surface contaminations) is evaluated in the interval (2700-3900) keV (excluding ^{190}Pt peak region from 3.2 to 3.4 MeV)
- **0.020 ± 0.001** counts/keV/kg/y reduction of a factor ~6 wrt Cuoricino

Dark matter sensitivity



Spin-independent signal: nuclear recoil of target nuclei via DM elastic scattering in keV region





CUORE background as derived from a test detector:

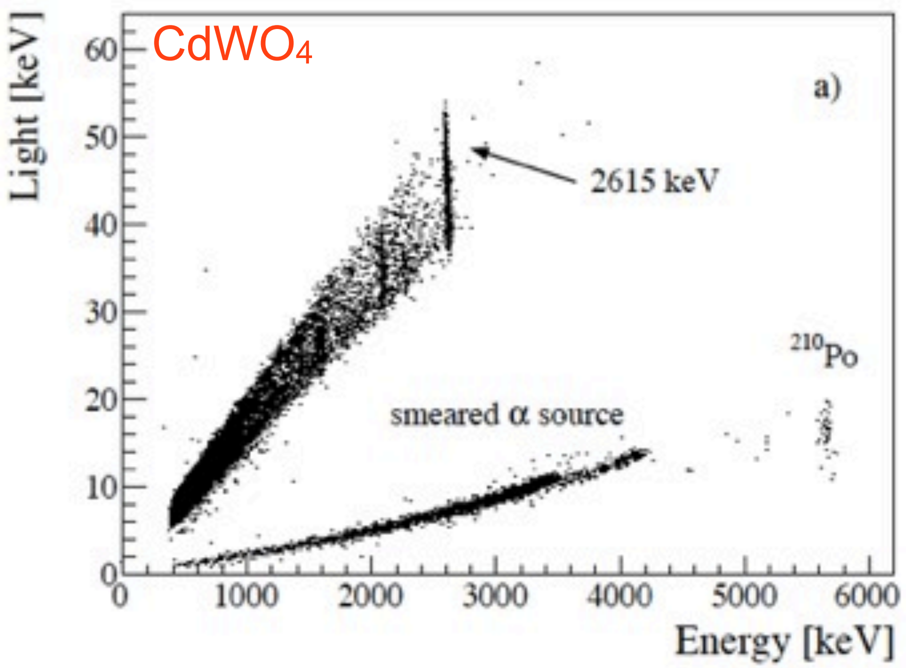
- high rate

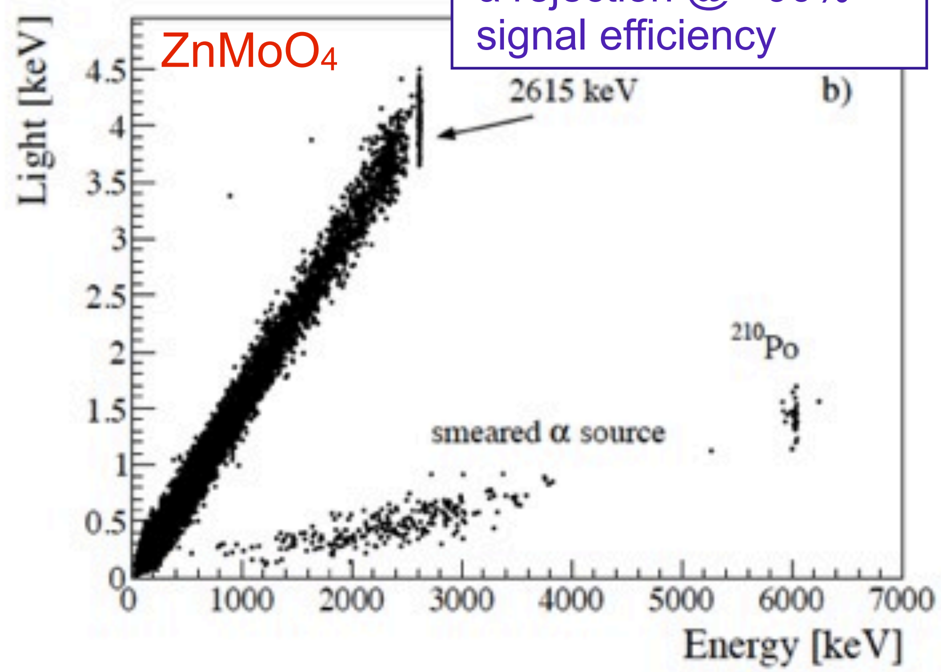
$\longrightarrow$ differential rate modulation

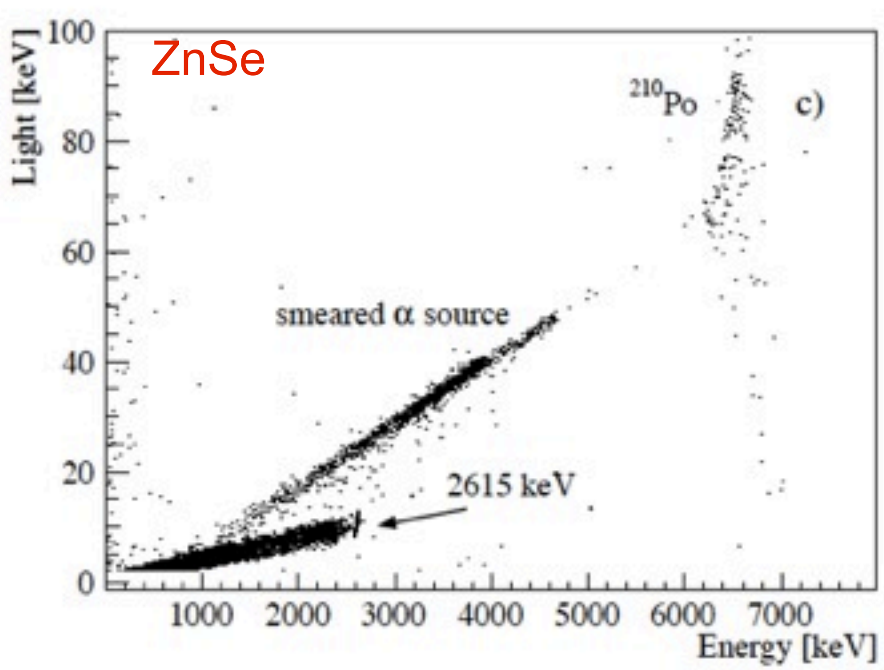
α/β discrimination

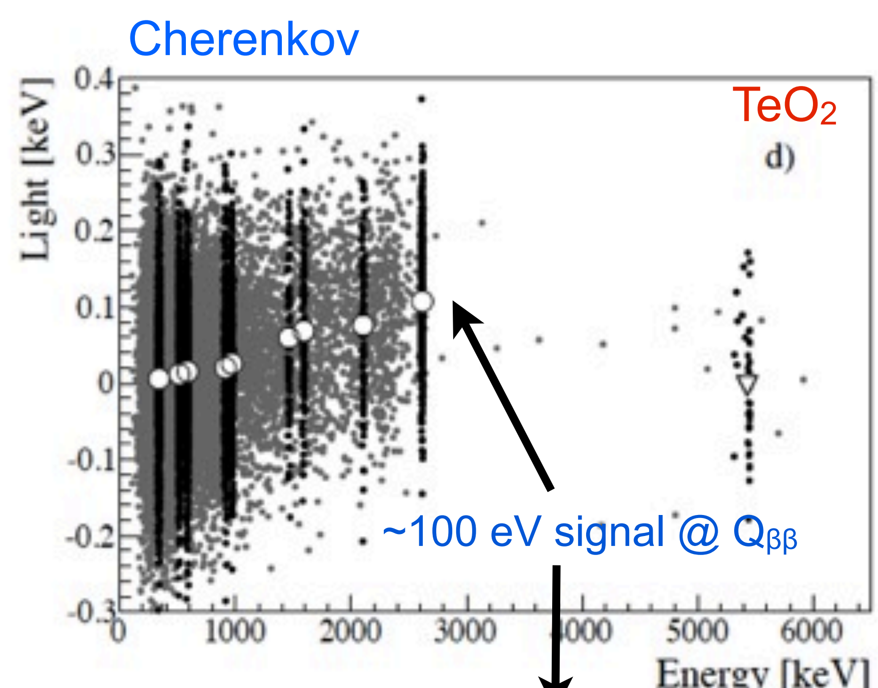
from: D.R.Artusa et al., arXiv:1404.4469 [hep-ex]

Demonstrated >99.9% α rejection @ >90% signal efficiency









Requires ~20 eV resolution for >99.9% α rejection @ >90% signal efficiency

(a) C. Arnaboldi et al., 34, 143 (2010)
(b) J. Beeman et al., Phys. Lett. B 710, 318 (2012)
(c) C. Arnaboldi et al., 34, 344 (2011)
(d) J. Beeman et al., Astropart. Phys. 35, 558 (2012)

Cherenkov light or scintillation to distinguish α from β/γ:

- $^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO4$ and $Zn^{100}MoO_4$
- more rejection power needed

Critical element: light detector